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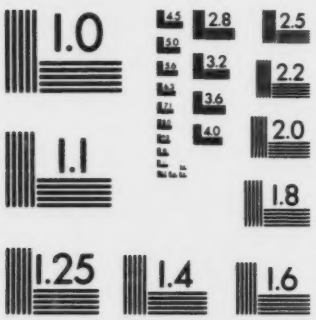

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STUDY TO CONSIDER THE INSTALLATION OF A SUPERCONDUCTING DC PROPULSION MOTOR INTO CCGS D'IBERVILLE

By:

ARCTEC CANADA LIMITED
#16, 6325 - 11th Street S.E.
CALGARY, Alberta
T2H 2L6

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TRANSPORTATION DEVELOPMENT CENTRE
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MONTREAL, Quebec
H3A 2R3

THE CONTENTS OF THIS REPORT REFLECT THE VIEWS OF THE CONTRACTOR AND NOT NECESSARILY THE OFFICIAL VIEWS OR POLICIES OF THE TRANSPORT CANADA TRANSPORTATION DEVELOPMENT CENTRE.

PROJECT TEAM

The project team for Arctec Canada Limited was composed of:

D. (Dusty) R. Miller

Jason E. Edworthy

E. J. LeCourt

Wilf H.G. Wlochal

and others

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17. Résumé

La société Arctec Canada a procédé à un examen de la salle des machines et des autres espaces intérieurs du NGCC d'Iberville, afin d'étudier la faisabilité d'y installer un groupe propulseur en courant continu à supraconducteurs. Ce groupe, conçu par la International Research and Development Company Limited du Royaume-Uni, sera prêt pour installation en 1984.

On a constaté que le groupe propulseur pourrait être substitué au moteur bâbord actuel, sans nécessiter de rénovations importantes, et qu'il y a suffisamment d'espace dans la salle des machines pour loger les appareils nécessaires à la production du courant continu et au maintien du moteur aux températures de supraconductivité.

Le rapport comprend un devis fonctionnel, un calendrier provisoire de réalisation et un programme d'essais.

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17. Abstract

Arctec Canada examined the CCGS D'Iberville and evaluated the engine room and other below deck areas for feasibility of installation of a superconducting DC propulsion unit. This unit is designed by International Research and Development Co. Ltd.,(U.K.) and will be available for installation in 1984.

It was found that the existing port engine would be replace with the DC unit without major renovations, and that sufficient space exists in the engine room for the generation and auxiliary equipment required to maintain the motor at superconducing temperatures.

Functional specifications suggested implementation schedule and test plans are presented.

18. Key Words	19. Distribution Statement
Superconducting motor, icebreaker conversion, DC electric marine motor, marine propulsion	Limited number of copies available from sponsoring agency

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SUMMARY

This report represents the results of the study to consider the installation of a superconducting propulsion motor in the existing icebreaker CCGS d'Iberville. The study was undertaken by funding from Transport Canada Transportation Development Centre (TDC).

The study considered the installation of an existing superconducting motor, rated at 5.86 MW already built by IRD in the U.K under funding from the Ministry of Defense, on the existing port shaft line of the icebreaker. The report also considers the installation of the life support system, principally the helium compressor, cold box and associated cryogenic piping, in place of the existing steam engine.

In order to achieve these study objectives a team from ACL visited the vessel and conducted an on-sight investigation of the room available and blocked out the equipment that would be required to install a new engine. After visiting the ship, the ACL team identified the removal of existing equipment on board the vessel on the port side and the installation of new equipment on the port side.

It was concluded after that visit that it was practical to install the motor and its associated life support system on the port shaft line of the icebreaker in the location of the present main engine. The power units for the electrical power were to be two diesel generators sets. mounted in the upper portion of the engine room casing. A list of structural modifications was developed to allow the installation of the equipment and an estimate of the time and cost of this conversion was prepared.

As a result of this study. it is considered practical to install a superconducting motor on the port shaft line in the location of the present main engine. The motor could be mounted on the existing tank top, with minimal modifications, and would have a similar performance to the present steam engine. The development plans for the converted ship were prepared and comments provided on the actual conversion of the ship.

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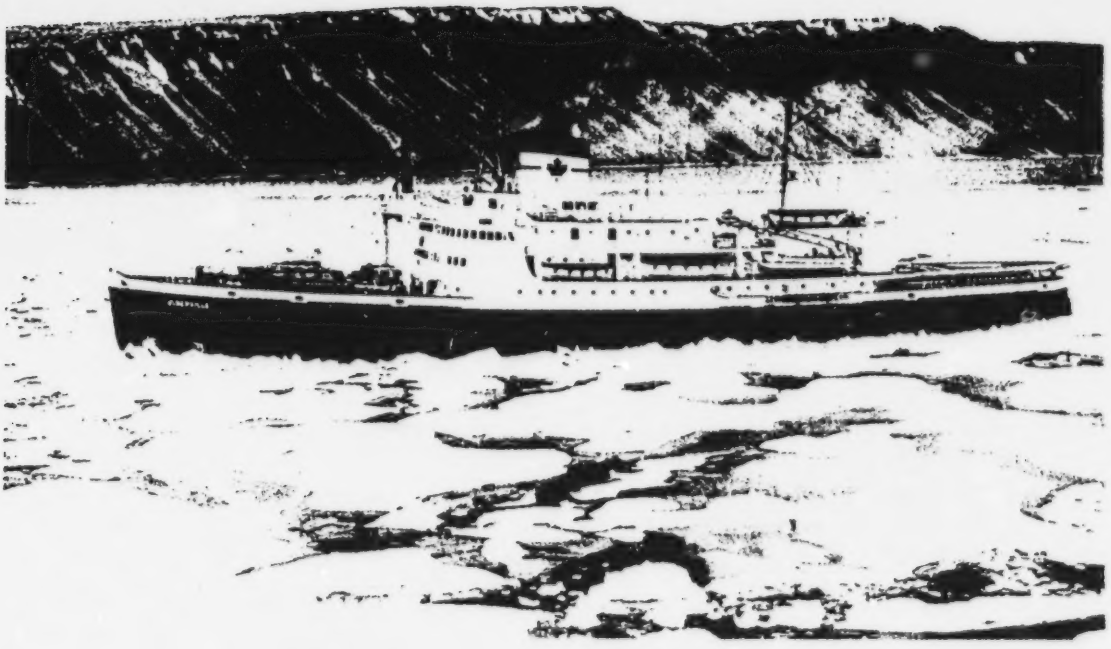


"On another occasion the CCGS "D'IBERVILLE" was also retained in the Arctic to investigate ice formation and to assess the possibility of season extension at Milne Inlet through either Navy Board Inlet or Eclipse Sound. On that particular occasion CCGS "D'IBERVILLE" remained in the area until October 23, 1967 and subsequently experienced very great difficulty to reach open water due to the heavily ridged and rafted pressured ice conditions prevailing at the eastern end of Eclipse Sound."

Extract from a letter from Captain J. A. Gallant recording late season experiments by CCG icebreakers in the Lancaster Sound area.

CCGS D'IBERVILLE

1. INTRODUCTION

The propulsion systems of icebreakers experience loadings and operational maneuvers far beyond those experienced by normal ships. Load fluctuations and rapid thrust reversals occur constantly due to ice piece ingestion by the propeller. During a typical 90 second ramming routine, the propulsion plant must go from full power full speed ahead, to stop, to full astern, to stop and back to full ahead. Consequently, propulsion systems in icebreakers have evolved in some unique ways, as designers and researchers have looked for a combination of higher power, faster maneuvers, ease of maintenance and a low volumetric requirement with lightness. Most icebreakers are now limited in their operations not by power, but by range; i.e., limited by the amount of fuel able to be carried on board. This last requirement has become more important as more power is installed without a corresponding size increase.

Initially, steam reciprocating engines were used for icebreakers, and because of their excellent torque/propeller revolutions and quick maneuvering capability, they remained preeminent until the 1940's. Since then, most icebreakers have used electric drive systems, initially DC/DC, then AC/DC, and lately consideration has been given to AC/FFC/AC. DC propulsion motors give excellent service, but they are limited to about 12 MW per armature by reason of current density. In addition, they are very large and heavy.

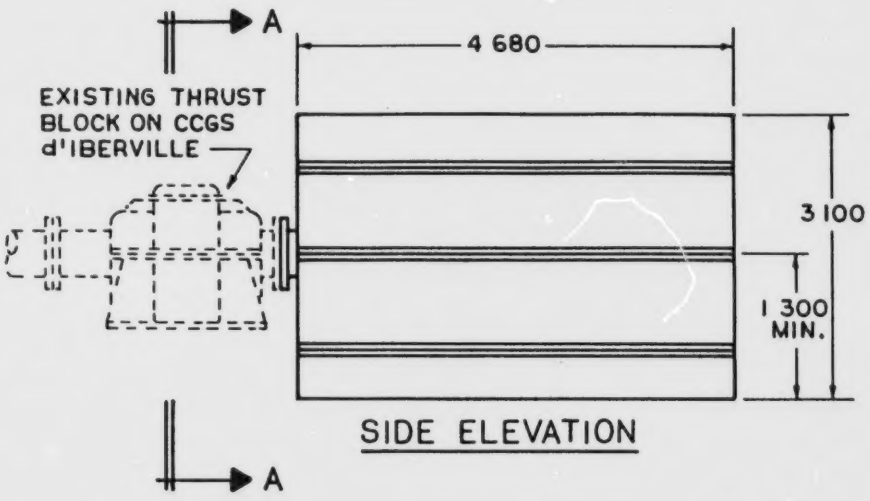
The search for the ideal icebreaker propulsion motor continues. The newest contender in the race now, again, uses DC motors, but removes their electrical limits by superconduction of the stator or field coils. Superconduction requires the maintenance of the field coils at a temperature of below about 6°K, so extensive refrigeration capability is required. Superconducting DC motors have now been demonstrated at relatively small powers, but have shown excellent reliability and very good power output characteristics. The MOD/IRD motor, originally designed and sized for 25 MW output power, is the subject of this report. The authors were charged to produce a functional or outline specification for the installation of this MOD/IRD motor, completed to 5.86 MW output power, into the port engine of the Canadian Icebreaker CCGS d'Iberville. If this conversion of the ship is undertaken, it is intended to use the vessel as a floating, fully operational test bed for the motor, and to thus prove the application of this motor principle to icebreakers and other high demand marine power plants.

2. PRESENT STATUS

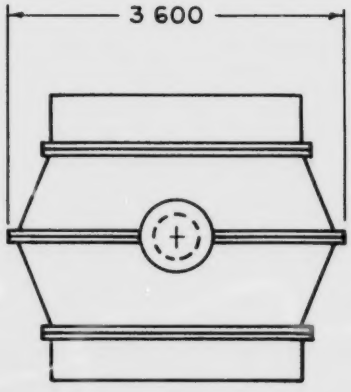
2.1 Super Conducting Motor and Life Support System

The motor considered in this project is the British MOD-funded, International Research Development Co. Ltd. (IRD), developed, homopolar superconducting DC motor (see Figure 1, opposite). The present design is sized for 25 MW of power capacity, however due to its modular construction it may be fitted to operate at lower power. It is presently rated at 2.24 MW (3000HP) with one set of field coils. The armature, which at present has not been constructed, will have the requisite number of current collection rings to allow the motor output to become 5.86 MW (7855 HP) which is a suitable power level for the present application. The development of the motor has passed through the experimental stage and is currently in a testing stage. The motor coils, cryogenic operations and associated hardware are in place and operational. The rotating outside armature and current collection systems are designed but not constructed, due to funding withdrawal by MOD. IRD have been considering alternative methods to obtain funding to allow the completion of the motor. MOD have advised IRD that the program can continue only with Canadian participation. It is anticipated that the Canadian participation would be the provision of a test vehicle (perhaps the icebreaker d'Iberville, if this feasibility study has positive results), while the UK participation would be some $\$3 \times 10^6$ to complete the motor and conduct static tests. IRD states that approximately one year is required to prepare the motor for delivery to a research vessel.

The motor life support system consists of a helium refrigerator/compressor unit, a cooling unit and associated piping and controls. These systems have been satisfactorily operational for some time, but are undergoing constant revision and refinement. Within the last few months, the existing motor components (ie. the coil, cryostat and cryostat support structure), have been successfully cooled and maintained at their cryogenic operating temperature of below 6°K. ARCTEC CANADA have formally inquired of MOD regarding their position on the motor and its support systems coming to Canada and participating in a demonstration project on board a ship. By a telex reply, dated 14th of July, 1983, MOD advised us that they would not be directly involved since IRD had been charged with conducting the negotiations on behalf of the UK government. To date the most preliminary discussions on this subject indicate that an amicable solution will be available if Canada decides to proceed with this physical conversion of the ship.



SIDE ELEVATION



VIEW A–A

OVERALL OUTSIDE DIMENSIONS OF
25 MW (PROJECTED) MOD/IRD MOTOR
(DIMENSIONS EXPRESSED METRICALLY)

Figure 1 MOD/IRD Motor Outline

The diagram Figure 2, (opposite) reproduced from the IRD technical memorandum which is included in this report as Appendix I, shows the output characteristics of the IRD/MOD motor. In para 5.3 of that IRD memo, the solid line OB is identified as the torque curve for the proposed motor. The dotted curve BDC shows the desired torque capability of twice rated; however, the text states that the proposed motor is not so designed. In the opinion of the authors of this ARCTEC report, this should be a requirement for the demonstration motor in as much as it will be mandatory for future icebreaking. An ice milling load torque characteristic for the propeller should be developed, and a corresponding design requirement for ice milling should be defined. The motor should then be designed, built and tested to meet this icebreaking requirement.

It must be noted that the present external dimensions and weight of the motor are appropriate for a 25 MW machine and that a custom designed 5.85 MW machine would be expected to be considerably smaller and lighter, at perhaps about 2m x 2m x 2m x 15t.

Figures 3, 4 and 5 (overleaf) give the present approximate dimensions and estimated weights of the S/C motor, cold box and compressor respectively.

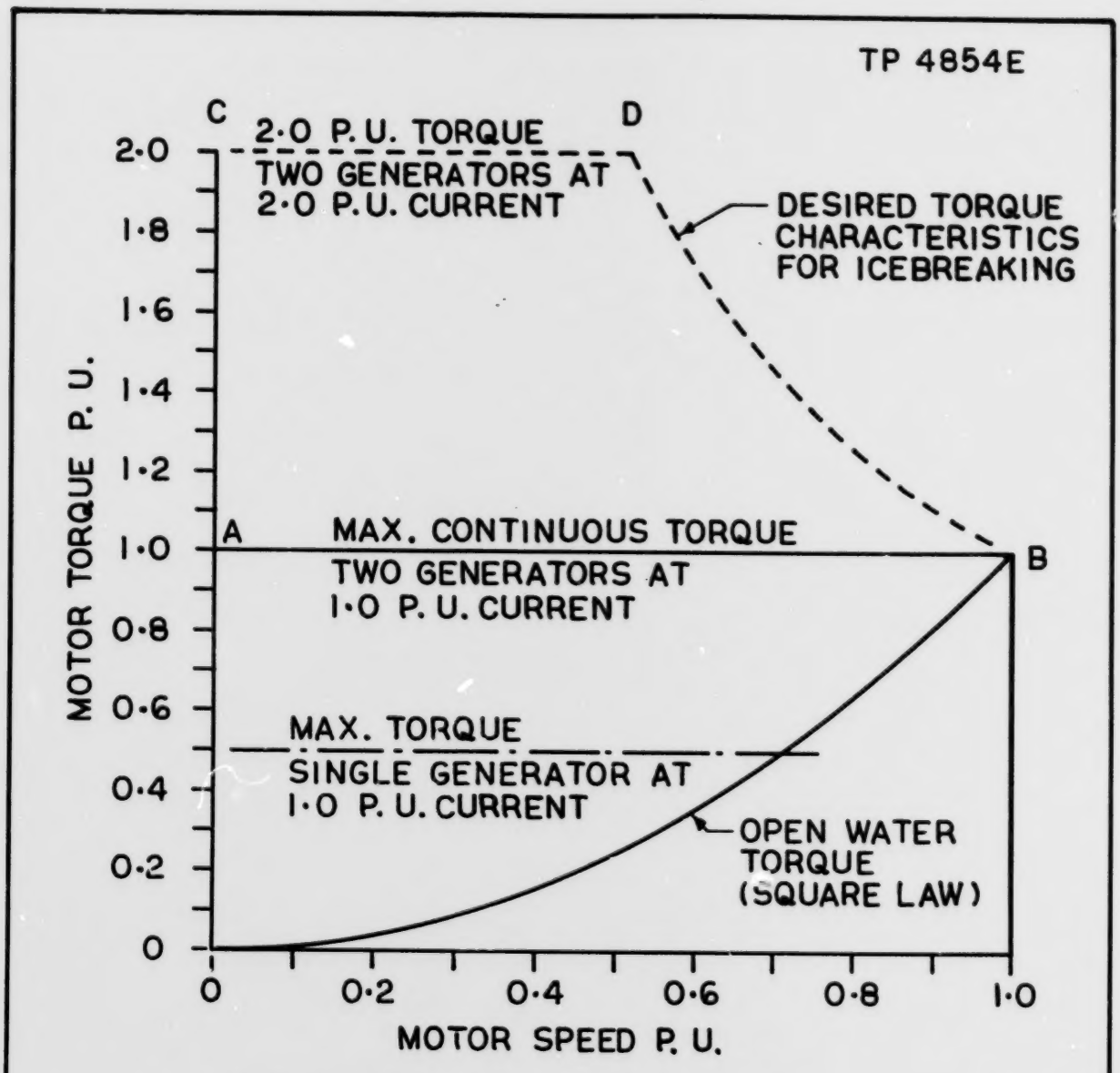


DIAGRAM SHOWING RELATIONSHIP
BETWEEN TORQUE AND MOTOR
SPEED FOR THE MOD/IRD MOTOR

Figure 2 Torque Vs. Speed Graph

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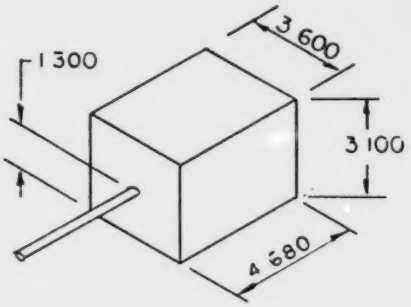
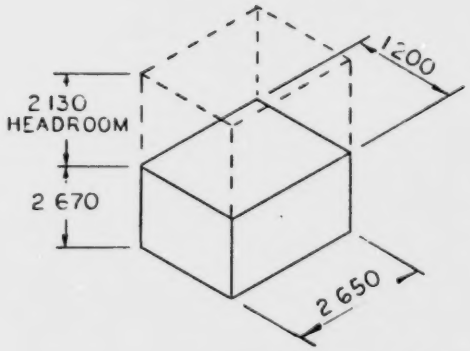


S/C MOTOR

WEIGHT: 58 TONNES
RATING: 5·86 MW (7560 HP)
SPEED: 162 RPM
VOLTAGE: 250 - 260 V
CURRENT: 27·5 kA

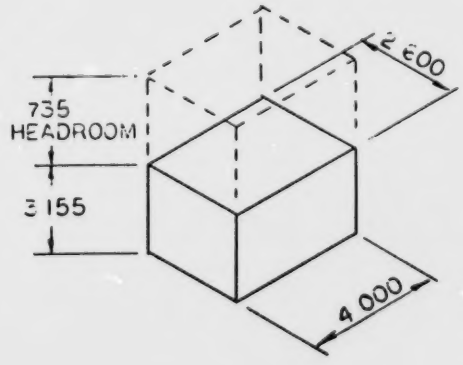
Figure 3 S/C Motor Dimensions



REFRIGERATOR COLD BOX
AND CONTROL PANEL

WEIGHT: 1.5 TONNES

Figure 4 Cold Box Dimensions



HELIUM COMPRESSOR
AND DRIVE MOTOR

WEIGHT: 6·0 TONNES
POWER CONSUMTION: 150 kW/h
SUPPLY: 440 V 3 PHASE
FREQUENCY: 50 HERTZ

Figure 5 Compressor Dimensions

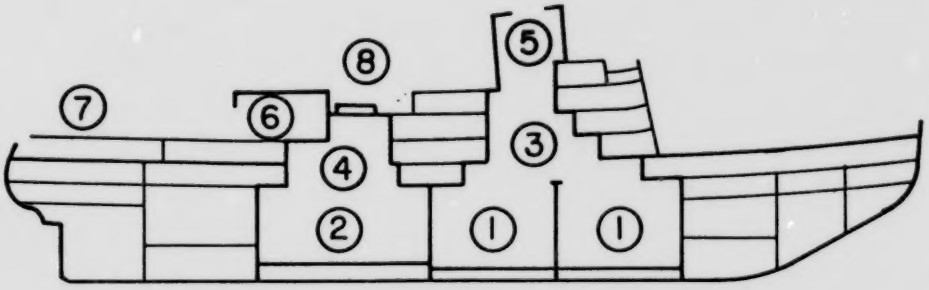
2.2 CCGS d'Iberville

In 1953, the Canadian Coast Guard (CCG) took delivery of the world's largest icebreaker of that time: CCGS d'Iberville (see Figure 6, Profile CCGS d'Iberville). At 94.5 m long, the vessel has a displacement of 10,100 tonnes and a nominal installed main engine power of 10,800 IHP (8,060 kW) from her two 6 cylinder steam reciprocating main engines. The steam supply came from eight "Scotch" firetube boilers operating at 1,600 kPa. The main engines/boiler were designed for operation in an "overload" condition at 15,000 IHP (11,200 kW).

After becoming surplus to CCG requirements in 1981, the vessel was laid up by Laurentian Region personnel in Basin Louis at Quebec City. The vessel passed into the jurisdiction of Crown Assets for disposal. Despite two separate circulations requesting proposals to purchase, no purchaser has come forward and the vessel is still afloat in Basin Louis.

During the lay-up preparations. all housekeeping and support systems had been drained and the vessel cleaned. All windows, doors and ventilations had been locked and covered. All valves had been lifted off their seats and adjacent flanges cracked and wedged. Consequently the visiting project team (See 3.1), found the vessel in very good condition. The general observation from the team was that the vessel could return to service should she be required. After a review of the condition of the main propulsion system with Mr. Jacques Mondy, Fleet Engineer, we were advised that the port engine had some main cylinder problems and was probably beyond repair but that the starboard engine was operable. All the boilers were also considered to be operable. The main steam system, while cross-connected, was designed with the 4 port boilers feeding the port engine and the 4 starboard boilers feeding the starboard engine.

Based upon this information regarding engine condition, it was decided that the port shaft line was to be considered as the prime candidate for installation of the S/C motor. Most of the engine room and boiler room layout was symmetrical; however, on the starboard side at the level of the upper engine gratings was a free standing engine lubricating oil tank, which would have required relocation had a starboard installation been contemplated.



℄ PROFILE OF CCGS d'IBERVILLE
SHOWING INTERNAL ARRANGEMENT

1. Main Boiler Rooms - four boilers in each.
2. Main Engine Room - two steam engines.
3. Boiler Uptake Casing.
4. Main Engine Room Casing.
5. Funnel.
6. Helicopter Hangar.
7. Helicopter Deck.
8. Engine Room Skylight.

Figure 6 Profile CCGS D'Iberville

3. VISIT BY ACL TEAM TO VESSEL

3.1 Description of Visit

A two day visit to the C.C.G.S. d'Iberville at Basin Louis, Quebec City, was made on July 8 and 9, 1983. Attendees included:

Mr. W. McCloy	Project Electrical Engineer, Polar Icebreaker Project, CANADIAN COAST GUARD
M. J. Mondy	Fleet Engineer, Laurentian Region, CANADIAN COAST GUARD
Mr. D. R. Miller	Senior Principal Engineer, ARCTEC CANADA LIMITED
Mr. J. E. Edworthy	Senior Scientist, ARCTEC CANADA LIMITED
M. E. J. LeCourt	Senior Principal Engineer, ARCTEC INCORPORATED

The present status of the vessel and its propulsion system were investigated (see Section 2.2), and details of a potential installation of the S/C Motor were studied.

On the first day, detailed drawings of the ship were studied and mock-ups of the S/C Motor and Support System were used to estimate equipment positioning and sizing.

The existing equipment, available room and access paths were measured on the ship and rough estimates of optimum positions discussed.

During the second day, discussions with Mr. Mondy detailed the present status of the ship and its systems. On board, positions of the new installations were measured and marked, and, with Mr. Mondy, necessary equipment was noted and avoided for installation. In this way, the optimum positioning with the fewest modifications was identified.

3.2 On-Site Observations

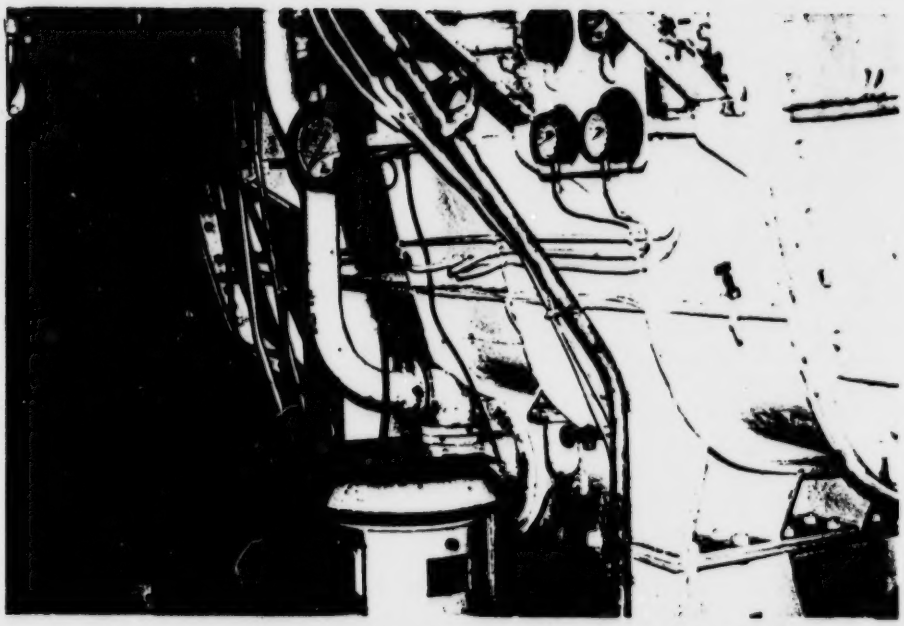
3.2.1 Engine Room Floor Plate Level

In the main engine room at floor level, the space was visualized after the removal of the port main engine, the port condensor and its associated sea water and steam piping, the port circulating and extraction pumps and their piping, the harbour pump and its piping and the port main feed pump and its piping (see Figure 7, Main Condenser). By measurement in the main engine room, it was apparent that the S/C motor would then be able to fit immediately ahead of the existing port thrust block (see Figure 8, Port Thrust Block). This was desirable since the existing shafting and bearings would then remain exactly "as is". However the height of the motor below the shaft centreline would necessitate a recess of about 300 mm deep being cut into the tank top plating and support floors. With the very high present tank top height of 1676 mm (5 feet 6 inches) this was considered to be acceptable with no reservations.

Outboard of, and immediately adjacent to, the motor, enough room was available between frames 60 and 84, (i.e, about 9.15 m), to install (from aft to forward), the dynamic breaking resistor, the reversing switches, the rectifier banks and the transformer banks. This arrangement was very good since the DC conductors would then be very short and direct in their routing. The individual items mentioned were measured out along the floor plates to confirm this arrangement.

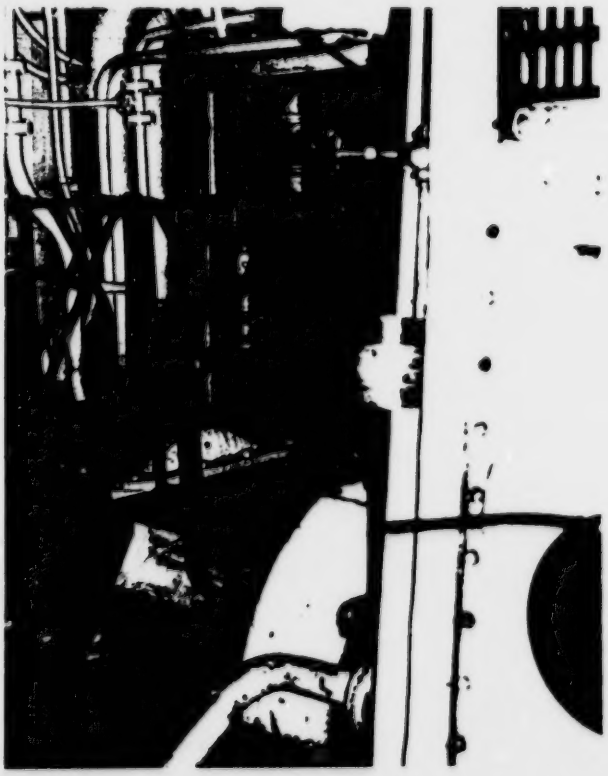
It is also desirable to have the cold box and the helium compressor as close to the motor as is practical. Initial measurements indicated that there was insufficient room forward of the motor to install the life support system. After discussions with Fleet Engineer Mondy, it was agreed that the port engine gauge board, the harbour pump (frame 87) and the main feed pump could all be removed without affecting the operation of the starboard main steam engine. These removals allowed ample space for the cold box and compressor to be installed immediately forward of the S/C motor. Because of the height of the compressor, it would require a recess in the tank top to allow it to fit below the generator flat immediately above.

In conclusion, this arrangement of the motor and its associated electrical equipment seemed to be very compact and efficient.



Photograph of Main Condenser Inside Face
Looking Aft and Outboard

Figure 7 Main Condenser



Photograph Looking Outboard and Aft, Showing Port Thrust Block and Aft End of Existing Main Port Engine

Figure 8 Port Thrust Block

3.2.2 Boiler Room

Having agreed on the machinery items that could be installed in the port side of the present engine room (see Section 3.2.1), it was now required to locate the two 3600 kW diesel generator packages and their switch and control boards.

Initially, the team had considered the removal of two boilers from the after boiler room and using this space for the diesel generators. Such an arrangement would have required the AC conductors to penetrate the intervening bulkhead (Frame 94) between the after boiler room and the engine room. The removal of the two boilers would have required them to be dismantled into small pieces and probably removed through an opening cut in the side shell of the vessel. This was considered to be relatively labour intensive and consequently expensive. After removal of the boilers, some work would then be required to modify the main exhaust trunking and insulation. While this work is normal shipyard practice, a considerable amount of staging would be required to allow the workers access to the underside of the main trunking. Again, it was considered that this would be relatively expensive.

Although the removal of two boilers would undoubtably provide enough room to install the two diesel generator packages, it was not obvious how the exhaust gas from the diesel engines could be ducted away through the already filled casing. The consideration of an overboard discharge of the exhaust gas was again considered to be a relatively major modification to the vessel.

During discussions with Fleet Engineer Mondy, some considerable discussion took place upon the main steam distribution piping. It was not immediately obvious what the effect of the removal of the connections from the two deleted boilers would have upon the steam circulation. Since the steam piping is large in diameter, constructed of copper, and insulated, it was believed that these modifications to the main steam supply could be expensive.

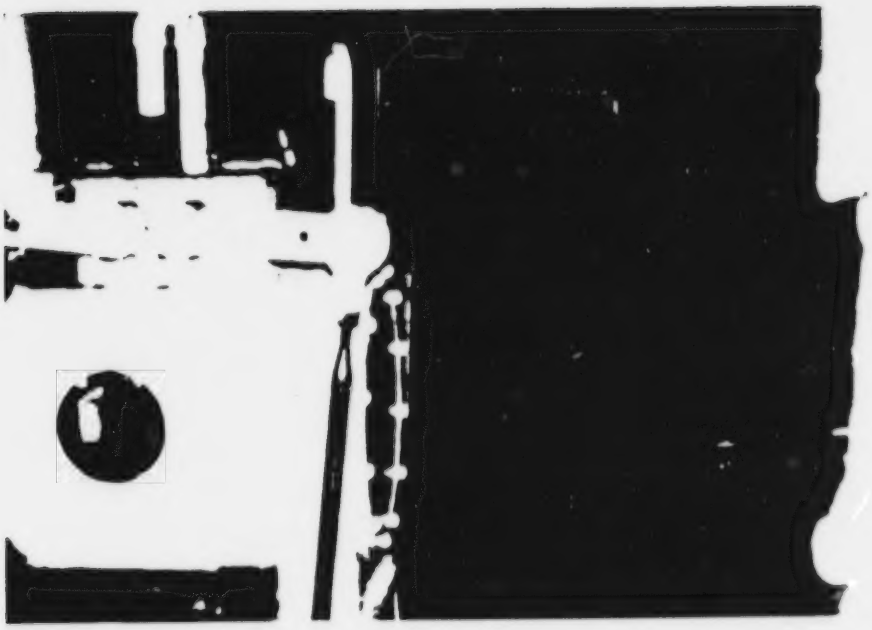
Thus, it was concluded that, if possible, these modifications and problems should all be avoided by considering and identifying an alternative location for the diesel engine/generator packages. The alternative location considered was in the upper portion of the port engine room (see Section 3.4).

3.2.3 Upper Port Engine Room

Having concluded that installation of the two diesel/ generator units in the boiler room would be difficult and probably costly, consideration was given to finding an alternative location. After some consideration and discussion between all the team members, it was decided to consider installation at the level of the upper engine room gratings (about 6.1 m above baseline) This would be between Frames 60 and 79 on the port side, in the area vacated by the condensor and the upper portion of the port main engine (see Figure 9, Generator Flat Level). This location would require the construction of a new steel deck outboard from about 600 mm off the centreline to the side shell. An examination of the adjacent structure, including the pillars at Frames 60 and 84 at about 4.4 m off the centreline, led to the conclusion that the structure would be relatively simple and easy to tie in with the existing generator flats.

To confirm this arrangement, measurements were made along the present gratings using estimates of the base size of the diesel generator, obtained from a manufacturer's catalogue, allowing about 1000 mm between the diesel engines. To keep the overall unit size to a minimum, it was decided to use a Vee-layout engine with 16 cylinders. Among the advantages of this location for the new diesel generators is that there is very easy and direct ducting for all exhaust gases and radiator cooling air. Access can be obtained from the open deck adjacent to the engine skylight down the open casing to the engine top. As an additional advantage, the length of the AC conductors could also be very short, with the AC generators located almost immediately above the transformers.

Thus, it was concluded, with the concurrence of all the team members and Fleet Engineer Mondy, that this location and arrangement in the engine room at the level of the present generator flat was the best available for this test program.



Photograph Looking Outboard to Port
at the Upper Grating Level

This is the position of the new generators.

Figure 9 Generator Flat Level

3.3 Installation Difficulties

The difficulties inherent in installing the Diesel/Generator sets in the present boiler room are as follows:

a) AC conductors must penetrate the main subdivision bulkhead on Frame 94.
b) Two boilers must be cut up into small pieces and manhandled out of the ship.
c) Modifications are required to the main boiler exhaust ducting and its insulation.
d) Modifications are required to the main steam piping.
e) Exhaust gas ducting from the diesel engines would be very difficult.

4. SCHEMATIC ARRANGEMENT

4.1 General

After some considerable discussion between all the team members, Mr. McCloy and Dr. Appleton, the Power Schematic diagram (Figure 10), shown opposite was developed and agreed to. As is often the case, it contains many compromises, however we believe that it represents a workable option within the Canadian test context. Inherent in many of the choices made during the development of the diagram was the realization that the program should represent the best combination of: the minimum amount of conversion to the chosen ship, the use of "standard" equipment to allow for future re-use by the Canadian government, should they so require, and the use of equipment that would be familiar to the eventual testing and operating personnel (probably CCG, if d'Iberville is eventually used).

It should be noted that the system shown opposite has to a large degree been "tailored" to the vessel d'Iberville, principally to her propeller characteristics and space availability. If an alternative ship is to be chosen as the test vehicle, the system design and sizing will have to be recalculated.

The power of the motor and of the system shown, has been based on the following "design point", as quoted on the drawing 590-M-501, "Arrangement of Shafting":

a) 4.03 MW at 145 rpm and
b) 5.86 MW at 162 rpm.

The existing propeller will determine the operating conditions. Before any further design work is undertaken, the propeller characteristic curves must be obtained. These should be available from the original design files; or, if not, approximate characteristics can be determined from a description of the propeller diameter, pitch, number of blades, and blade area. In addition, ice milling design criteria should be developed and included as requirements for the propulsion system.

In the following sections each of the major components of the system is described in some detail regarding its performance.

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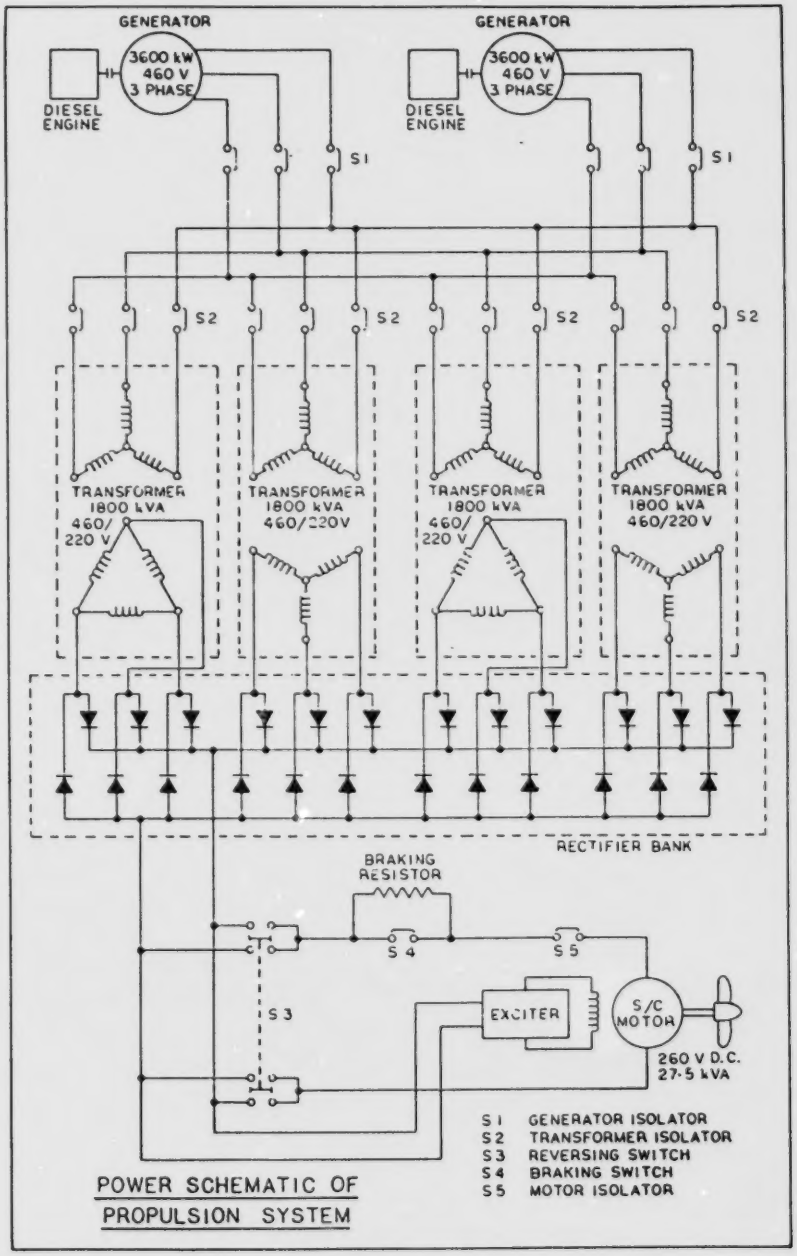


Figure 10 Power Schematic

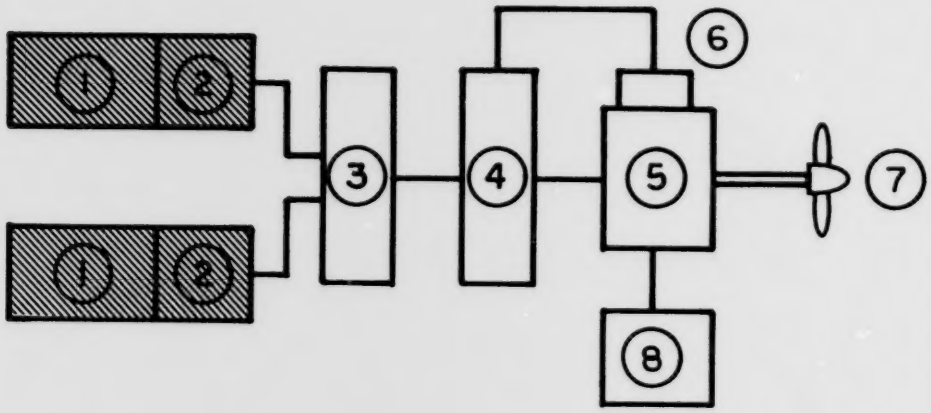
4.2 Prime Mover and Generation Equipment

The S/C motor requires an adequate source of appropriate electrical energy to power it. Although a variety of system configurations are possible, the authors suggested that system components meet the requirements with the greatest program economy.

It is proposed that the prime mover be two diesel fuelled engines (see Figure 11, Diesel Engines Generator, opposite), each using a "V 16" configuration. This prime mover system is of sufficient power to drive the required generating equipment. The chosen engine configuration provides a compact machine of low profile with high efficiency. Diesel powering provides good fuel economy and the machinery is commonly available. Additionally, skills for installation, service and maintenance are also commonly available within the Canadian maritime community.

The fuel supply for the new diesel engines will be provided from a new ready use tank connected to the existing diesel oil transfer system (see Section 5.3).

The generating equipment proposed is field-excited alternator type, 3600 kW power at 460 volts, 3 phase. This machinery will feed power through a switchboard to the transformers. This type of equipment is commonly used in marine vessels, and service skills are readily available. The diesel-generator sets proposed have advantages for re-use at the termination of the research project, because they are commonly used types. The possible need for re-use of the components of the system was identified by Mr. McCloy.



1. Diesel Engines (2)
2. AC Generators (2)
3. Transformers
4. Rectifiers (AC to DC)
5. S/C Motor
6. Motor Excitation
7. Ship's Propeller
8. Braking Resistor

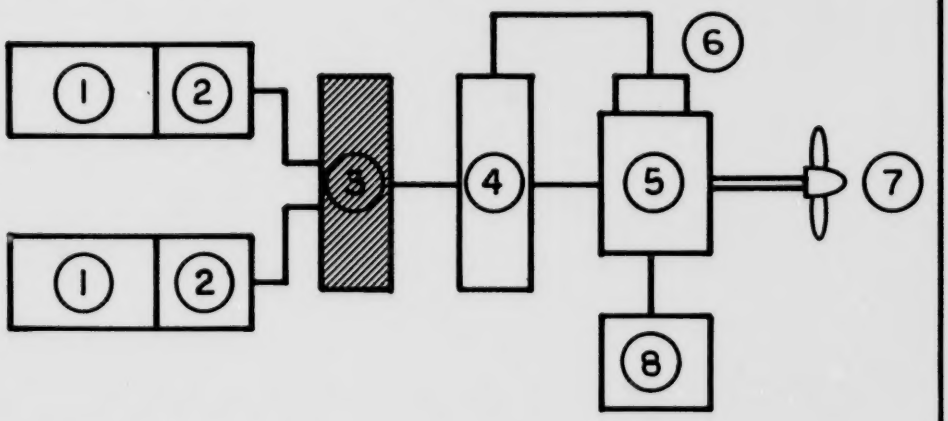
Figure 11 Diesel Engines & Generators

4.3 Voltage Transformation

The design AC voltage required for the S/C motor before rectification is about 190 V. The output voltage of the conventional generator sets, ie. 460 V, must then be transformed to this lower value.

Standard 460/220 volt transformers are proposed. These can be tapped at 190 volt output without difficulty. Again the use of "standard" items of electrical gear can facilitate their re-use at the termination of this experimental program.

Four sets of transformers (see Figure 12, Transformers, opposite), will be coupled to the common line, drawing 1800 kVA each. As shown on the Power Schematic (Figure 10) two transformers will be connected y/y and two connected y/Delta. This design will result in the equivalent of 6 phase AC power entering the rectifier units.



1. Diesel Engines (2)
2. AC Generators (2)
3. Transformers
4. Rectifiers (AC to DC)
5. S/C Motor
6. Motor Excitation
7. Ship's Propeller
8. Braking Resistor

Figure 12 Transformers

4.4 Current Rectifiers

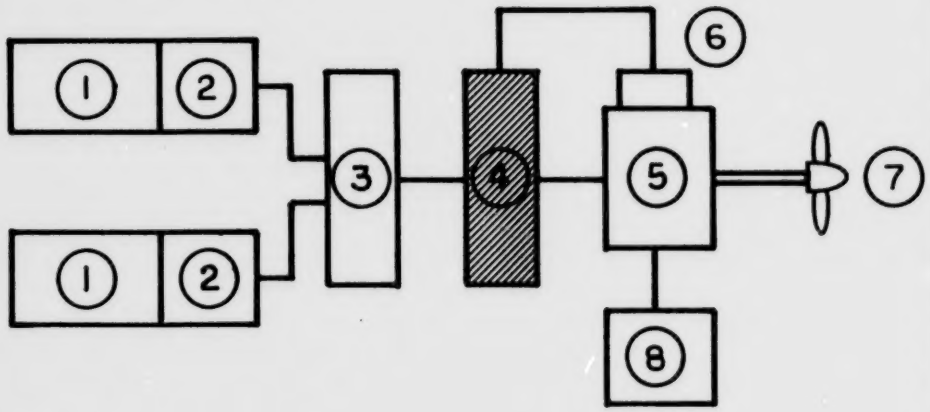
The S/C motor, since it is in homopolar configuration, requires Direct Current (DC) power. Thus it is necessary that the AC supply from the transformers be rectified to DC before connection to the motor (see Figure 13, Rectifiers, opposite).

Two sets of 6 phase rectifiers will be installed to provide nearly "flat" Direct Current voltage.

The rectifiers will require special design and careful manufacture due to the high current loads which they will be handling. Cooling requirements and space limitations have been considered in this design.

All rectifier units will feed to a common, large capacity DC bus.

The motor input power requirements are 252 Volts at a current of 27.3 kA.



1. Diesel Engines (2)
2. AC Generators (2)
3. Transformers
4. Rectifiers (AC to DC)
5. S/C Motor
6. Motor Excitation
7. Ship's Propeller
8. Braking Resistor

Figure 13 Rectifiers

4.5 Ancillary Equipment

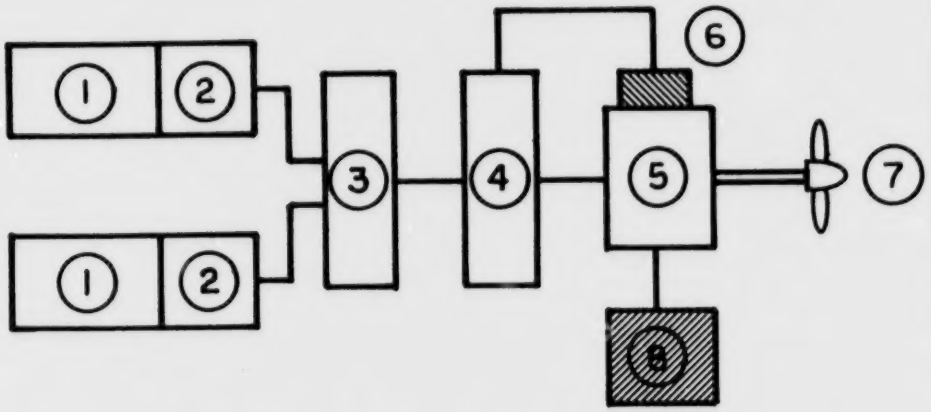
The S/C motor requires an excitor system for its field coils (see Figure 14, Motor Excitation & Braking Resistor, opposite). These coils are the portion of the motor which is maintained at cryogenic temperatures. The excitor draws a relatively heavy current from the direct current bus during the initial motor start-up (approximately 12.5 kW, 10 V), but draws a fraction of this charging load during operation.

The S/C motor uses a resistance braking system to halt the motor quickly. The braking resistor is placed next to one of the motor terminals. It will consist of a large air cooled resistance bank, where energy can be dissipated through the generation of heat.

Extensive use is made of switching gear throughout the total power system in order to allow control, regulation and safe operation of the S/C motor.

Transmission of AC electrical energy from the generating equipment to the power conditioning equipment requires cabling of high capacity, but not of special production.

Transmission between the rectifier bank and the terminals of the S/C motor will require a specially designed and manufactured bus bar system of high current capability. The transmission distance required is kept to a minimum in the proposed system design to reduce line losses and keep costs minimal. First estimates from IRD suggest that the two main DC conductors to the motor will each consist of 6 bars (12 total) of copper measuring 40 mm by 100 mm and spaced 40 mm apart; and that each set of 6 bars being a "built-up" conductor and will be separated from the adjacent conductor by about 900 mm. These conductors operate at ambient temperatures and should not require any active cooling and ventilation, unless they are arranged or shielded in such a way that natural air circulation is restricted. It is suggested that during the detailed layout of these conductors, a space 1300 x 500 mm should be allowed for installation.



1. Diesel Engines (2)
2. AC Generators (2)
3. Transformers
4. Rectifiers (AC to DC)
5. S/C Motor
6. Motor Excitation
7. Ship's Propeller
8. Braking Resistor

Figure 14 Motor Excitation & Braking Resistor

4.6 Controls

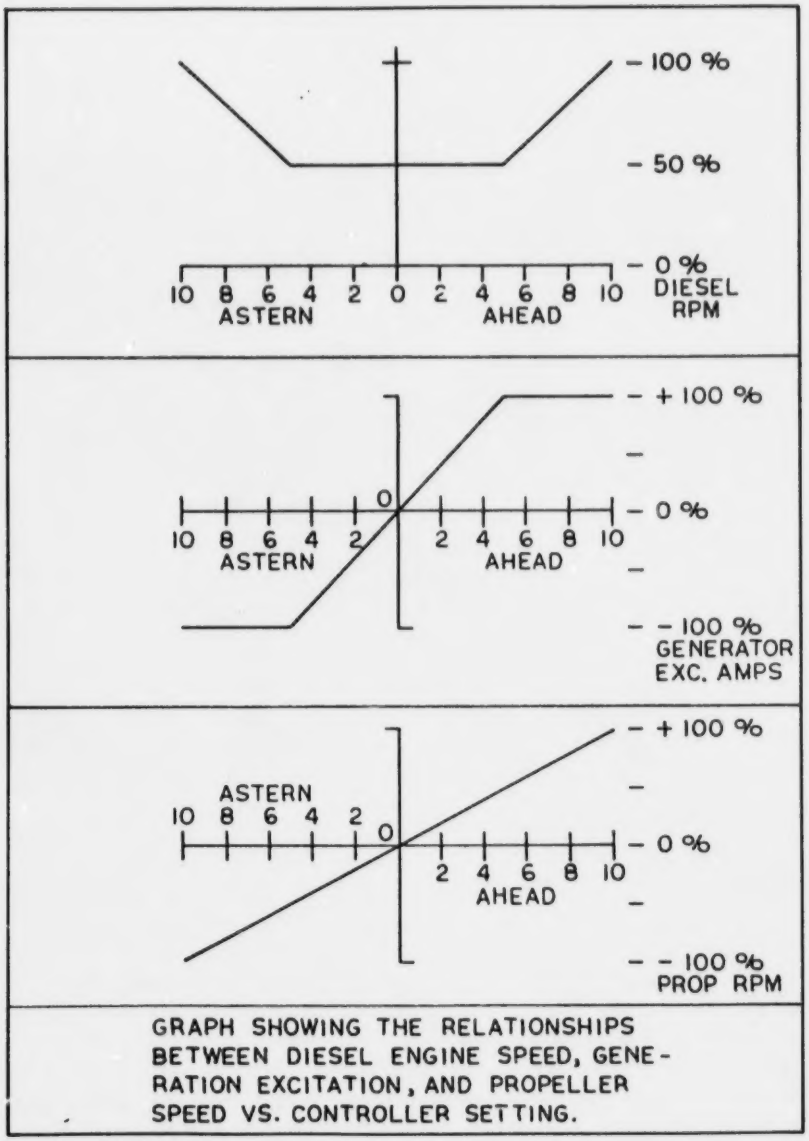
Because of budget limitations, the requirements for the power system controls were considered in principle only. Discussions held between Messrs. Lecourt and McCloy concluded that the design for the control system requires special attention; however, it was also concluded that the control system was certainly within present and proven technology and practice. This statement in general would apply to the diesel engine speed control and the generator field excitation control. Since all this equipment is custom designed, there would be a relatively high purchase price for the total control system. A very preliminary cost estimate would suggest a price in the order of $250,000.

The principle of the speed control of the propulsion motor is shown diagrammatically, (Figure 15, Controller Setting Graph, opposite). At zero or low propeller rpm, the diesel speed will be maintained at idle speed, say in the order of 500 or 600 rpm. Control of the propeller speed will be obtained by variations in the generator excitation flux, from 0 to maximum. At this point of maximum flux and about half speed on the generator, the propeller will be at half speed and the output power will be 12.5 per cent of full rated power. As the controller setting continues to increase, the generator excitation flux will be maintained at the maximum level and the generator speed (and diesel speed) increased until full speed is achieved.

The control scheme described above is suitable for ship maneuvering both in open water and in ice. An additional automatic control system is required for ice milling. This control will sense motor current and automatically reduce generator excitation to limit the motor current to a predetermined value. This value will be set based on the torque requirements for ice milling.

It is recommended that a machinery plant simulation on a digital computer be performed to analyze the control system. The simulation should include the dynamics of the diesel engine and its governor, the generator, transformers, rectifiers, and the motor. The propeller characteristics and the dynamic behaviour of the ship should also be included. The simulation can be used to analyze crash reversal in open water, ramming in ice, and ice milling.

The Main Engine Control Board (see Figure 16, Control Board, (overleaf) will be retained for the Starboard Engine control.



GRAPH SHOWING THE RELATIONSHIPS BETWEEN DIESEL ENGINE SPEED, GENERATION EXCITATION, AND PROPELLER SPEED VS. CONTROLLER SETTING.

Figure 15 Controller Setting Graph

Photograph Looking to Starboard at
Main Engine Control Board

PORTION MARKED * - to be removed and
essential gauges
relocated.

Figure 16 Control Board

5. SPECIFICATION FOR CONVERSION

5.1 General

It is the intent of Section 5, in conjunction with the remainder of this report, to present an outline or functional specification for the installation of a superconducting homo-polar motor, rated at 5.86 MW output, on the port shaft line of the existing CCG Icebreaker d'Iberville. The installation or conversion of the vessel is arranged in such a manner that all modifications and labour will take place within the confines of the main engine room, generally upon the port side. This specification text does not address items outside the engine room.

The following sections of text are arranged such that items to be removed are addressed first, then the new structural items which will be required, followed by the installation of the new equipment and finishing with the pre-operational testing and training. Outline drawings based upon the as-fitted machinery arrangement have been prepared and form an integral portion of this outline specification. Because of a lack of definition in many factors and systems, it is not possible to be definitive at this time in many areas of the conversion. Instead, the authors have chosen to present the conversion in principle and in intent. It is intended that when a system or piece of equipment is addressed by name, that that name includes the total system and all its facets. In this way it is intended to transfer the responsibility for satisfactory operation of this system, under both tests and operating conditions, to the prime contractor of the conversion. The prime contractor should satisfy himself, before accepting the contract, that he understands the requirements to satisfactorily "make all the components of, and the total system, all work", under the arduous and special conditions imposed by an icebreaking ship being operated in her normal manner.

5.1.1 Outline

After removal of the port main steam engine from the vessel, along with the port condenser and its associated piping and pumps, the new S/C motor will be installed forward of the existing port shaft thrust bearing. Outboard of this and on the same level, will be the transformers, rectifiers and switches required. Immediately forward of the S/C motor will be the liquid helium system cold box and the reciprocating compressor. Above the S/C motor at the present generator flat level, a new deck portion will be constructed and 2 diesel/generator sets mounted thereon. The switchboard for the essentially self-contained system will be mcunted immediately aft of the new generators and forward of the existing ship's service generators.

5.2 Removal of Present Equipment

Preparatory to the installation of the new equipment and machinery, it will be necessary that the existing port main engine and many of its support systems within the engine room be removed. The new equipment will be installed in the vacated spaces. During the removal of any item of equipment or machinery, it is required that all adjacent piping, electronics, controls, and pneumatics also be removed back to the next position of isolation, which could be either a valve or an electrical connection box. In the case of a valve, a blank flange shall be installed on the exposed face of the valve. Where possible, gratings, walkways, structural seats, brackets, pipe clips, etc. will be removed by burning torch to within 20 mm of the original main structure parent metal.

The list of equipment on the opposite page (Table 1, Items to be Removed) identifies the main items of machinery and their systems to be removed as part of this conversion. The terminology used reflects the "as fitted" Machinery Arrangement, Drawing 590-M-505. It should be noted that item 14, the harbour pump, is not shown on this drawing, having been a retro-fit. It should also be noted that item 15 - the main feed pump port - must be retained by the Contractor after its removal and supplied to the ship as a direct spare for the starboard main feed pump. An oily water separator is also presently installed in the vessel, about 4800 mm off the centreline to port at about Frame 86.5. This item shall be retained "as is".

ITEMS OF PRESENT EQUIPMENT TO BE REMOVED

ITEM	NAME	DIST. OFF C.L. (mm)	FRAME
A) At the Engine Floor Level Port Side			
1.	Aux. Cir. Pump Starter	7,000	58.5
2.	Aux. Extr. Pump Starter	7,000	61
3.	Main Extr. Pump Starter	7,000	63
4.	Aux. Cir. Pump	5,900	62
5.	Main Condenser	6,300	70.5
6.	Aux. Extr. Pump	5,600	67.5
7.	Main Extr. Pump	5,200	72
8.	Main S.W. Cir. Pump	5,000	79
9.	Starter Pump	7,200	79
10.	High S.W. Suction	7,000	81.5
11.	Low S.W. Suction	4,500	82
12.	Main Condenser Piping	5,500	76-82
13.	Main Engine (Port)	2,300	60-80
14.	Harbour Pump	3.200	87
15.	Main Feed Pump	1,000	87.5
16.	Engine Gauge Board (P)	2,000	83.5
B) At the Generator Flat Level			
17.	Main P. Steam Piping	4,100	70
18.	P. Exhaust Steam Piping	6,000	65-75
19.	Condenser Discharge Piping	7,500	75.5
20.	Workshop Bulkheads	6,200	56-60
21.	Welding Machiner	5,500	59.5
22.	Davis Filter (P)	1,800	52.5
23.	Precoat Tank	1,500	5
24.	Precoat Pump	750	5
25.	Sorbo Cell Box	2,750	55.5

Table 1 Items to be Removed

5.3 Structural Modifications

After all the equipment and its seating noted in Section 5.2 has been removed from the vessel, a number of structural modifications which need to be made to the engine room before the new equipment can be installed. These additional structural items are detailed opposite (Table 2, New Structural Items Required); it is understood that any item which is omitted, but will be necessary for the successful execution of the conversion and subsequent test program shall be included in the conversion.

All these structural additions should be constructed of scantlings and welding standards compatible with the existing ship, i.e. over normal scantlings to full heavy icebreaker standards with full continuous welding used throughout, without any exception. Extensive tripping brackets and plate stiffeners are required in all new structures and, where possible, the ends of all members should be connected to the adjacent structural member. Particular care should be taken to resist the cracking and fatigue failures generated by the heavy load cycles incurred constantly by the structure during icebreaking operations.

The seats for the new propulsion motor, (Item 1.2, Table 2, opposite), shall be designed for the worst combination of overload torque, thrust reversals, and the high and low frequency vibrations induced by the propeller. Epoxy resin chocking material shall be used between the motor footings and the top plate of the support seats.

The seats and top support for the reciprocating type helium compressor, (Item 3), require particular care because of the height, weight and overturning moment of the unit. This compressor should be mounted on resilient mounts, top and bottom.

The main diesel/generator sets mounted upon the new deck, (Item 5.1), shall be delivered from the manufacturer, bolted down to a rigid base. This base shall then be mounted by resilient mounts to the main deck structure.

The new diesel engines will require a higher grade of fuel than the present boilers. As part of this conversion, some main hull fuel tanks must be converted to diesel oil fuel and connected (if not already connected), to the present diesel oil transfer system. The pump for this is located at Fr. 110 port. This 5.25 kW pump (switch 9 in power panel P8) has a capacity of 30 m^3 per hour. This pump will then supply diesel oil fuel, for the two new diesel/generator sets. to a new 4 m^3 "ready use" tank to be installed in the upper engine room casing.

LIST OF NEW STRUCTURAL ITEMS REQUIRED

1. AT THE PROPULSION MOTOR
   - 1.1 Recess in the Tank Top Directly Below Unit
   - 1.2 New Support Seats and Collision Chocks

2. AT THE COLD BOX
   - 2.1 New Seats

3. AT THE HELIUM COMPRESSOR
   - 3.1 Recess in Tank Top Directly Below Unit
   - 3.2 New Seats on the Tank Top
   - 3.3 New Top Support Structure Under the Generator Flat

4. AT THE ELECTRICAL EQUIPMENT OUTBOARD OF THE MAIN S/C MOTOR
   - 4.1 New Seats on the Tank Top
   - 4.2 New Top Supports Below Generator Flat

5. AT THE NEW DIESEL/GENERATOR SETS
   - 5.1 A New Heavily Scantlinged Steel Deck (see Section 3.2.3) Including Two Pillars Below at about Frame 74.
   - 5.2 New Seatings and Collision Chocks

6. AT THE NEW SWITCHBOARD
   - 6.1 New Seatings at the Deck
   - 6.2 New Top Supports at the Underside of the Upper Deck

7. IN THE UPPER CASING OF THE E.R.
   - 7.1 A New Ready Use Diesel Oil Fuel Tank for the Diesels

Table 2 New Structural Items Required

5.4 Installation of New Equipment

When the new seatings, detailed in Section 5.3, have been installed, the main items of new equipment can be entered into the engine room. Once this is done, construction of the remainder of the associated support systems can be commenced. Because of potential access problems, it is suggested to the contractor that the sequence of installation of main machinery items follows the suggested sequence of Table 3, Items to be Installed, opposite.

Some of the main items with which care must be taken are the AC power conductors from the generators to the switchboard, then to the transformers and rectifiers. The main DC conductors from the rectifiers to the motor require exceptional care because of the high current load at 27.5 kA (see Section 4.5). To reduce electrical losses, the main DC conductors must be kept as short and as direct as possible. All electrical cables and conductors shall be attached to their support structures at more frequent intervals than would be required by normal ship standards.

The piping associated with the helium compressor and cold box shall be installed using the highest standards to avoid the loss of the use of the propulsion motor, should any failure or leak occur in the helium or refrigerant locks. Appropriate arrangements shall be incorporated into these pipe runs to absorb the thermal and mechanical shocks likely to be imposed upon them by the liquid helium cooling and the icebreaking operations. The main exhaust gases from the 2 diesel generators shall be piped up the casing through the deck to the exhaust above the navigating bridge deck level, aft of the W.T. cabin. This exhaust piping shall be insulated and installed to the normal CCG Icebreaker standards. The diesel cooling arrangement shall be by air-cooled radiator. Proper ducting shall be installed to either supply cold air to, or exhaust hot air from, the radiator. This air supply/exhaust duct shall terminate on the open bridge deck in the vicinity of frame 80 in a cowl vent. Since the electrical equipment, mainly the transformers and rectifiers, will generate some heat during normal operation, appropriate arrangements shall be made to provide a cooling medium to the area in accordance with the recommendations of the equipment manufacturer. At present it is preferred that air be used for cooling, and if possible be drawn down from cowls installed on the bridge deck, and supplied to outboard of the equipment.

The installation of all equipment and systems shall be to the approval of the appropriate division of the Marine Safety Branch of the Candian Coast Guard of Transport Canada.

INSTALLATION OF NEW EQUIPMENT

Suggested Sequence:

1. HELIUM COMPRESSOR
2. COLD BOX
3. TRANSFORMERS
4. RECTIFIERS
5. MAIN REVERSING SWITCHES
6. DYNAMIC BRAKING RESISTOR
7. S/C PROPULSION MOTOR
8. SWITCH-BOARD
9. OUTBOARD DIESEL/GENERATOR
10. INBOARD DIESEL/GENERATOR
11. DIESEL EXHAUST SYSTEM
12. DIESEL RADIATOR COOLING SYSTEM

Table 3 Items to be Installed

6. IMPLEMENTATION

6.1 General Requirements

In order to proceed with installation of the S/C motor in a Canadian vessel, a general implementation plan must be formulated and followed.

The authors suggest that this plan would apply to installation in almost any vessel. For specific implementation into the CCGS d'Iberville, please refer to Section 6.2.

Initially, the remaining development work required for the S/C motor must be completed. Final design work is required to ensure that the powering characteristics match existing shaft and propellor specifications and performance. The controls should be designed and analyzed using a digital computer simulation of the propulsion machinery.

Importation details and shipping requirements should be arranged well in advance of scheduled departure from the U.K.

Detailed design, sizing and costing of ancillary electric gear and generation equipment must be started and the equipment ordered with sufficient lead time for delivery. Upon receipt of the final overall equipment dimensions, a check should be conducted upon the space and access required.

The receiving vessel must be prepared for re-fitting. Removal operations must be planned and scheduled, dry-docking times scheduled and ordered, and arrangements must be made for labour and materials. Similarly, installation must be planned with careful monitoring of schedules to coordinate timing.

Prior to installation of the S/C motor and gear into the vessel, any on-land static testing must be planned and scheduled, with consideration of shipments of all ancillary equipment.

Once installation is completed on the vessel, crewing and logistic operations suitable for the mission profile must be completed. During mission planning, all financial considerations must be accounted for.

The authors assume that local or southern testing of the refitted vessel would precede trials in the Arctic. Following completion of trials, the ship would be available to follow her mission profile in full operational mode.

6.2 Short Term Plan

This section specifically deals with requirements pertaining to refitting of the CCGS d'Iberville and installation of the S/C motor in her.

During completion of the motor development in the U.K., design study of the existing propellor and shafting characteristics will be required in order to match the motor performance correctly. This will ensure suitable operation of the motor in the vessel. This phase will likely take about one year to complete. A computer simulation of the propulsion system is required to analyze the dynamic performance of the system during maneuvering and ice breaking. Prior to its acceptance by Canadian authorities, the complete motor and support system shall demonstrate their reliability by successful compliance with the test items 1, Section 6.2.1.

Upon delivery to Canada, the motor will be scheduled for testing at the Naval Test Establishment in Montreal. This Canadian "bench test" program will be designed not only to test the motor and its sytems, but to provide a teaching and familiarization role for the operators in the ships trials to follow. When this phase is completed, the equipment will join the ship at the refitting yard.

Detailed specifications and costing of the exact configuration of ancillary equipment will be required during the first year. This will provide sufficient lead time for delivery and special design work for rectifier equipment.

Detailed specifications, estimates and costing for the installation on the d'Iberville will be developed during the first year. These will include deck removals, present engine and equipment dismantling and removals, new structures and decking, installation of new equipment and reconstruction of topsides. Re-commissioning of the vessel must also be considered.

During the two or less years with which short-term implementation is concerned, the complete sequence of the test program and the vessel mission profile during extended voyage type testing must be developed and approved. A suggested operational test program is shown opposite.

Approval by Marine Safety Branch of CCG must be obtained at several points during implementation.

6.2.1 Test Programs

Suggested test programs for S/C motor and its support system.

1. IRD testing in UK, shall include:
   - 6 hours each, astern and ahead, at the rated full load,
   - 1 hour each, astern and ahead, at 125% rated full load,
   - 100 sequences in less than 4.00 hours of; start, to full rated load ahead (for 30 secs), to stop (for 20 secs), to full rated load astern (for 30 secs), to stop (for 20 secs).

2. Canadian "bench testing" at Naval Testing Establishment, shall include:
   - 12 hours each, astern and ahead, at 100% rated output,
   - 12 hours each, astern and ahead, at 125% rated output,
   - 200 sequences in less than 17 hours of; start, to 10% rated output (for 30 secs), to 50% rated (30 secs), to 100% rated ahead (60 secs), to stop (10 secs), to 100% rated output reverse (60 secs), to 50% rated astern (30 secs), to 10% rated (30 secs), to stop (10 secs),
   - 50 "crash reversals" each in less than 8 secs of; from 125% rated output ahead to 100% rated output astern,
   - maintenance and operating procedures for all components of the system.

3. Basin trials. after installation in the ship, shall include:
   - 1 hour each, astern and ahead, at 40% rated output,
   - any demonstration and measurement trials required by Marine Safety Branch of CCG.

4. Ship reliability demonstration trials, south (at sea), shall include:
   - 24 hours continuous at 15% rated ahead output,
   - 24 hours continuous at 40% rated ahead output,
   - 48 hours continuous at 100% rated ahead output,
   - 6 hours continuous at 110% rated ahead output,
   - engine maneuvering trials repeating the sequence in 2) above, but for 100 cycles only,
   - 20 "crash reversals" as detailed in 2) above.

5. Ship trials in Arctic shall include:
   - operation of the motor as required by the mission profile of the vessel,
   - ice milling as generated by ship operations in multi-year thick ice and ramming of ridges and large floes.

6.3 Cost and Schedule

Within the available budget time for each item, it was not possible to develop a detailed cost estimate or schedule. In Sections 6.1 and 6.2, the various items of action required for implementation of the, conversion have been identified. Table 4, Budget (overleaf) shows the authors' opinion regarding a preliminary cost figure likely for the conversion. The total figure is about $\$8.6 \times 10^6$, excluding:

a) any work on the present (starboard) engine or its systems,
b) the transportation of the S/C motor from the U.K. or within Canada,
c) the cost of static testing of the S/C motor,
d) any maintenance or work on the ship not directly related to the S/C motor, and
e) any lease or rental payment relating to the use by Canada of MOD (U.K.) purchase equipment.

Within the budget figure quoted, there is $\$3.5 \times 10^6$ assigned directly to the purchase of new equipment, including the diesel/generator sets, transformers and rectifiers.

Regarding the likely time for implementation, again, a definitive estimate is difficult to prepare; however, in the opinion of the authors, the Table 5, Lapsed Time Estimate (Page 41), reflects a reasonable first level estimate. The lapsed time from assignment of a contract to prepare detailed drawings and specifications, and submission directly to the shipyards for estimation and contract purpose, is estimated to be 78 weeks. The physical conversion of the ship, including basin testing, is estimated at a further 39 weeks for a total of 117 weeks (2 years, 3 months) for the complete program.

Figure 17. Implementation Plan (fold-out), shows the interrelationship of the various program components, their lines of communications, and their chronological positions.

PRELIMINARY BUDGET COST ESTIMATE

NO.	ITEM	1983 COST ($ x 10^6)
1.	Preparation of Detailed Drawings and Specifications	0.500
2.	Drydock of Vessel to Remove Condensor Inlet/Outlet Valves	0.100
3.	Prepare Access to Engine Room	0.150
4.	Remove Equipment, as Detailed in Section 5.2	0.500
5.	Structural Modification. as Detailed in Section 5.3	0.750
6.	Install New Equipment, as Detailed in Section 5.4	1.250
7.	Purchase Two Diesel/Generator Sets	2.250
8.	Purchase Transformers	0.250
9.	Purchase Rectifiers	1.000
10.	Purchase Switchboard and Switches	0.500
11.	Purchase All Other Electrics, Controls	0.250
12.	Purchase and Installation of New Cryogenic Piping to Motor	0.100
	SUBTOTAL	7.600
13.	Contingency	1.000
	BUDGET ESTIMATE	8.600

Table 4 Budget

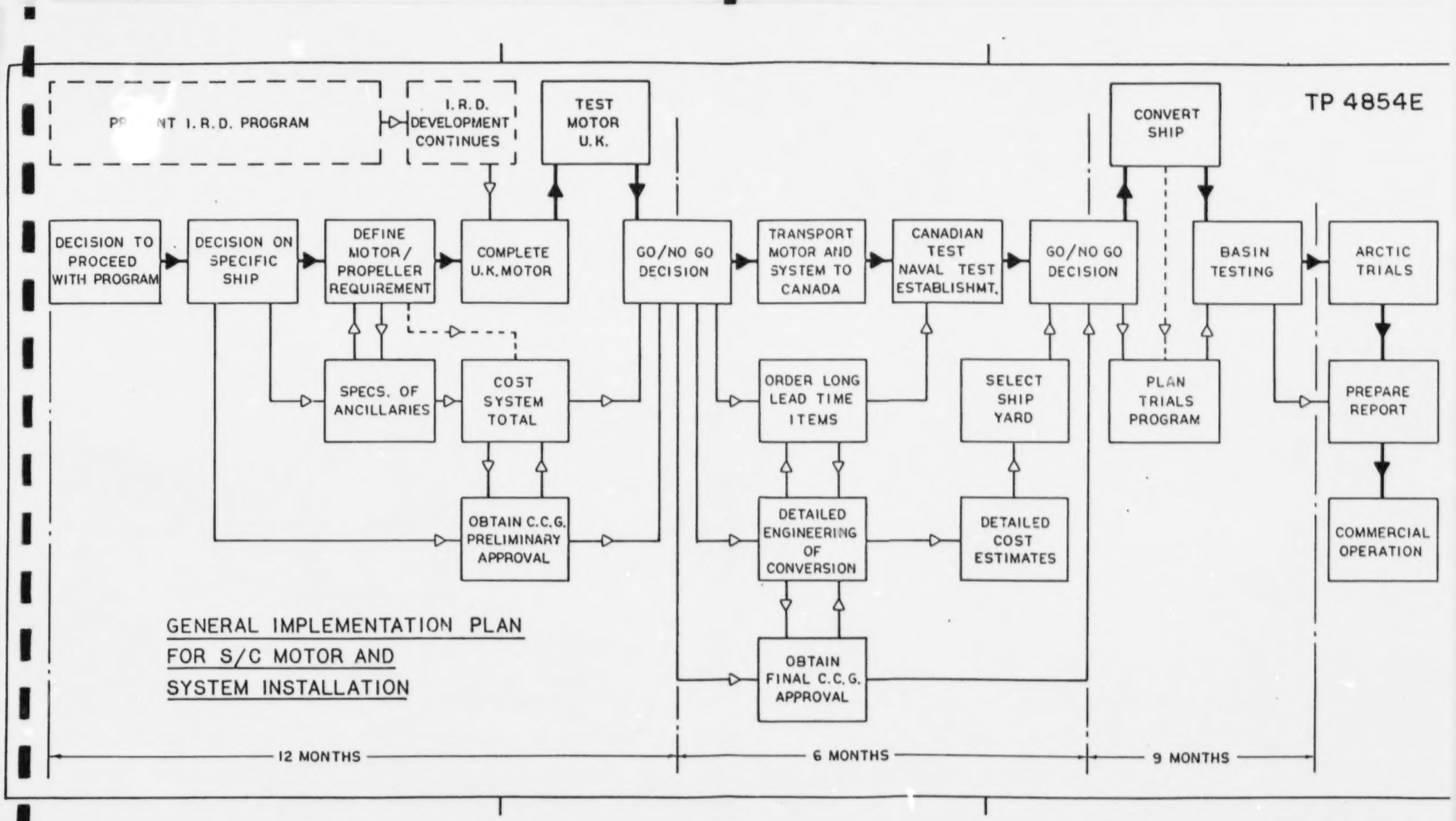


Figure 17 Implementation Plan

ESTIMATE OF TIME REQUIRED TO EFFECT THE CONVERSION OF CCGS d°IBERVILLE

NO.	ITEM	LAPSED TIME
	Preliminary Specifications and C.C.G. Approval, Cost Estimates. Specifications of Ancillaries and Motor/Propeller Requirements, and U.K. Motor Tests	42
	Contingencies	10
	SUBTOTAL PHASE I	52 Wks
	GO/NO GO DECISION	
	Shipment of Motor, Preparation of Drawings and Specifications, Canadian Motor Tests, Selection of Shipyard and Procurement of Bid Prices	12
	Detailed Cost Estimates, Final Engineering of Conversion and C.C.G. Approval, and Identification of Long Lead Time Items	10
	Contingencies	4
	SUBTOTAL PHASE II	26 Wks
	GO/NO GO DECISION	
	Order of Long Lead Time Items, Preparation of Ship for Conversion	3
	Drydock Vessel, Removal and Blanking-Off Ship Side Valves, and Removal of Equipment (see Section 5.2)	8
	Structural Modifications (see Section 5.3)	6
	Installation of New Equipment	12
	Basin Testing, Planning of Sea Trial Programs	4
	Contingencies	6
	SUBTOTAL PHASE III	39 Wks
	TOTAL LAPSED TIME FROM DECISION TO PROCEED WITH PROGRAM TO FINAL REPORT AND COMMENCEMENT OF ARCTIC SEA TRIALS	117 Wks = 27 Mths

Table 5 Lapsed Time Estimate

7. CONCLUSIONS

The project team for this work was charged by TDC with the production of a functional (outline) specification for the installation of the MOD (U.K.) motor into CCGS d'Iberville. Section 5, with its associated drawings, supplemented by the technical content of this report, addresses that task.

Supplementary discussions with TDC and CCG led to the request that we discuss the feasibility of the work in these conclusions.

Based upon our visit to the vessel and our knowledge of naval architecture, marine engineering and shipyard operations. we have no hesitation in concluding that the conversion described in this report is technically feasible and relatively easy. A major part of the work in shipyard will involve the removal of the present port main engine and its support systems. Since this engine is inoperative at present and the vessel is out of commission and not likely to be reactivated in its original form, this removed equipment can be discarded. This allows the shipyard to burn and cut the machinery, piping etc. down to manageable pieces of scrap for removal. When the equipment is removed, there will become available a large volume of space well able to accommodate all the new equipment coming in. The new arrangement of the S/C motor and its support systems is compact, and since it is essentially a self-sufficient system and <u>not</u> tied into the existing ship's service and control, no problems should be encountered. Head room above the equipment is sufficient for all ducting, wiring, exhaust etc. to be run without interference from any existing system.

Since the drawings etc. have been based upon the installation of the "big frame" motor, it follows that the installation of a custom-designed motor (at 5.85 MW) should be considerably easier, since it is much smaller.

The cost of the conversion has been estimated to be about $\$8.60 \times 10^6$, and the total lapsed time to be about 117 weeks.

Whereas it is the conclusion of the authors of this report that the installation of the S/C motor into the vessel CCGS d'Iberville is relatively easy, it must be born in mind that there are questions still remaining about the suitability of the motor installation. At present, these relate to the performance of the motor under icebreaking conditions. It is not clear, at this time, whether the motor torque output curve is of a suitable form for use in

an icebreaking ship. Before any decision is made regarding the installation of the motor into any ice transitting vessel, this factor must be addressed. In addition, the motor output and system reponse and control should be tailored to the specific vessel's propellers. This was not done in detail for CCGS d'Iberville under this contract.

APPENDIX 1

TECHNICAL MEMORANDUM

FROM I.R.D. DATED 14 JULY 1983

International Research & Development Co Ltd

Fossway Newcastle upon Tyne England NE6 2YD

Telephone 0632 650451

To See Distribution

From B. J. C. Grand

Technical memorandum

Date 14th July, 1983

IRD/TM/83- 198

EED/MGW/AP84/TM-210

CONCEPT OF THE MOD (UK) MOTOR AND DERIVATION OF TEST MOTOR AND SYSTEM FOR C.G.S. d'IBERVILLE

Distribution

Mr. D. R. Miller Arctec Canada Limited (3)
Dr. A. D. Appleton
Mr. T. C. Bartram
Mr. B. J. C. Grand
Project Control
Library

1. INTRODUCTION

The proposed test motor for Canada is an adaptation of existing hardware originally produced for the MOD (UK) Superconducting Motor Research Programme. Because of this, the proposed machine has overlarge dimensions and is of low voltage resulting in relatively poor efficiency for the required rating.

The concept of the MOD (UK) machine and the derivation of the motor for Canada are described below with a comment on 'frame size' potential in Section 4.2.

For quick reference major system components are listed in Table 1, a provisional motor specification in Table 2, and demands for a.c. electrical and cooling water services in Tables 3 and 4.

2. MOD (UK) RESEARCH MACHINE

The research programme was initiated to demonstrate the practicality of the superconducting d.c. machine concept by extended test operation of the field system and armature. The construction phase would also identify manufacturing routes and quality assurance requirements. It was thus defined that the physical dimensions would, as far as possible, model at full scale future production motors, e.g. 25 MW at 200 rev/min.

2.2 FIELD SYSTEM

Because it was not necessary to prove the Maxwell-Faraday Law of Electromagnetic Induction and output power was not important, the flux level produced by the field system of the research machine could be nominal. The decision was made therefore to utilise some existing superconducting coils of suitable diameter housed in a full size cryostat, the redundant space being filled with Tufnol packing. This provided the added advantage that testing with a full rated armature would be at low power (2-3 MW) and minimal cost.

2.3 ARMATURE

The armature dimensions were dictated by the field system defined above and the intention was to provide a current rating relevant to a 25 MW, 200 rev/min motor, i.e. about 20 kA. The armature was also to demonstrate multiple stages in series and brush/slipring performance.

3. DERIVATION OF TEST MOTOR FOR CANADA

The required rating was assumed to be 5.86 MW (7560 hp) at 162 rev/min (rating given on Davie S/B Drg. No. 590-M-501). If this rating can be reduced, modification to the outline design will improve efficiency as current reduces.

3.1 VOLTAGE

With the research motor field system the total generated back e.m.f. at 162 rev/min with a resonable number of stages is 222.75 volts.

3.2 CURRENT

For a net output of 5.86 MW the required current is 26.3 kA at the above back e.m.f.

3.3 EFFICIENCY

The estimated efficiency is 85.17% with the above arrangement. This low efficiency is well below that which would be achieved with a purpose designed machine, and is due to the low voltage resulting from the adoption of the research machine field system(see Section 4).

Allowing for the losses the conditions at the motor input terminals are estimated as 252.25 V and 27.26 kA; allowing for Transmission losses etc. this suggests a minimum rating for total rectifier output of 260 V and 27.5 kA d.c.

4. DIMENSIONS/WEIGHT

4.1 TEST MOTOR FOR CANADA

Motor overall dimensions are shown in Fig. 1. At the drive end a bearing is shown which will carry the journal load of the rotor. If the ship thrust bearing end float is less than $\pm$ 0.5 mm then it may be possible to locate the rotor with reference to the stator using solid couplings and suitable shafting. If, however, the main thrust bearing end float is greater than above, the motor drive end bearing will have a thrust element to locate the rotor accurately, and a suitable flexible coupling must be interposed between the to thrust bearings to avoid conflict.

The weight of the motor including the drive end bearing and special shaft is estimated at 60 tonnes. Of this weight the rotor is approximately 22 tonnes with a polar moment of inertia of about 2.7×10^4 kg m^2.

4.2 'FRAME SIZE' POTENTIAL

The machine dimensions are excessive for the 5.86 MW rating and are due solely to the adoption of the research field system. Typically, the 'frame size' should cover a rating up to about 30 MW at 162 rev/min with an efficiency of over 95%. Some minor adjustments of proportions could further improve on power output and efficiency.

5. PERFORMANCE

5.1 EFFICIENCY

Efficiency in the context of open water propulsion (cube law) is shown varying with speed in Fig. 2.

5.2 SPEED/POWER

Using two generators/rectifiers driven by two prime movers to supply power to the motor provides performance as shown in Fig. 3. Assuming each prime mover is rated for full half motor power and each generator/rectifier is rated for motor voltage and half motor current, limiting speed (cube law) on a single generator/rectifier/prime mover is just over 0.7 per unit with the generator at 1.0 p.u. voltage (i.e. about 0.35 p.u. shaft power); this is shown as point A on Fig. 3. With both generators operating full speed is reached at point B.

5.3 TORQUE

The torque characteristics of the proposed motor are shown in full lines on Fig. 4. The curve OB shows that open water (cube law) torque and the line AB shows that 1.0 p.u. torque is available continuously from the motor over the speed range.

Although the proposed motor is not so designed, Fig. 4 also shows in broken line a typical torque characteristic for an ice breaker shaft drive. Using the same prime mover ratings as before but with generators and rectifiers capable of 2.0 p.u. current, 2.0 p.u. torque is available from zero to 0.5 p.u. speed (line CD) and reducing from 2.0 p.u. to 1.0 p.u. torque over the speed range 0.5 to 1.0 p.u. (curve DB).

5.4 SHORT CIRCUIT CONDITIONS

One important function of protective systems in electrical networks is that of discrimination, which is the disconnection of faulty circuits from the overall network whilst leaving all healthy circuits operational. In the case of the proposed superconducting motor installation this criterion does not apply since the whole of the network is dedicated to one task. The only possible exception to this is in a multigenerator system operating at a load which could be met by fewer generators than are connected and fault occurring on a generator section of the

network before the point of common coupling. This type of fault may be adequately dealt with by the a.c. switchgear, or by removing the excitation from the appropriate generator and using a.c. isolators. This problem is eased considerably by the fact that the rectifiers block infeed to the fault from the healthy generators.

A fault at the motor terminals has been recognised as a serious event since it makes the system inoperable until rectified. Under this condition all operational generators feed the fault via rectifiers, a condition which is detectable and may be dealt with on the a.c. side as described earlier. Careful choice of generator reactance would limit the fault current to about twice full load current before any action is taken. The motor of course feeds the fault as it becomes a generator driven by its own inertia and that of the propeller and shafting plus feedback torque via the propeller due to ship motion. The worst case occurs when the motor was previously being driven at full speed. The nature of the motor is such that the current it delivers to the fault produces a braking torque at the motor and preliminary calculations show that a maximum current of about ten times full load flows from the motor after about 0.25 Seconds. The retarding torques stop the shaft in about 0.3 seconds and if as seems reasonable the motor and propeller have about the same inertia, then the shaft would transmit about five times full load torque. We are unable to comment on the effect of this and suggest that the shafting capability be assessed and consideration given to a shear coupling as a protective element. On detection of the fault the excitation of the motor would be removed. This is effectively a linear discharge over four seconds. The motor would be able to survive such an event.

In considering the issue of protection against this type of fault it is difficult to identify how a permanent fault could occur at the motor terminals. The case requires that the fault occurs whilst the system is operational; if the fault is put on before start up the system deals adequately with it. If one considers a spanner or similar object being dropped on the terminals by some means, then this would be blown off by a relatively small current.

If the object is by some means firmly wedged, then should it vapourise due to ohmic heating and the arc would be similarly expelled. It seems reasonable to assume that a major fault leading to the currents and torques calculated would be an extremely unlikely event especially as the calculation assumes a highly efficient connection between the terminals which must be almost impossible to achieve in practice with the system operational.

6. RECTIFIERS, GENERATORS AND PRIME MOVERS

The motor power supply will require two prime movers each driving an a.c. generator supplying d.c. power to the motor via rectifiers and a bus/switching system, the latter causing a voltage drop of the order of one volt. An outline system diagram is given in Fig. 5. These notes are framed in terms of exactly matching ratings being available working back from the propulsion motor rating. It is, however, appreciated that nearest 'off-the-shelf' machinery will be used and the propulsion motor will be designed to match the finally chosen prime movers/generators.

6.1 RECTIFIERS

The minimum rating of each rectifier is, say 260 V, 14 kA d.c. continuous.

6.2 GENERATORS

To provide a d.c. voltage of 260 V requires an a.c., r.m.s. line to line voltage of about 200 V, and the required generator continuous rating is about 3.6 MW. For generators dedicated to propulsion, the frequency is not significant, but prime mover speed must be considered in the selection. It is preferable to avoid the use of transformers to achieve the desired voltage. Thus, although this generator specification is non-standard as regards machines available commercially, there are at least two ways in which a suitable machine may be adapted.

a. Consider a machine of adequate power output with a standard voltage of 380-400 V at the desired prime mover speed. If this machine has numbers of stator slots and poles both divisible by 2, it should be possible to reconnect in two parallel paths, thus halving the voltage.

b. Consider a machine of adequate current capacity but designed for higher speed than the desired prime mover. Both voltage and power output will be modified by the ratio of desired speed to design speed. Method (a) may then be applied to halve the resultant voltage.

6.3 PRIME MOVERS

Allowing for generator losses the prime mover continuous rating required is just over 3.7 MW, say 3.75 MW.

7. CONTROL BASICS

7.1 SPEED CONTROL

With the motor in pre-set field mode, speed adjustment is achieved by control of supply voltage, the motor then drawing the current necessary for the torque requirement from the system.

Voltage control via diode rectifiers can be exercised by adjustment of prime mover speed, or generator excitation or a combination of these. Alternatively, thyristor controlled rectifiers can be used with constant generator voltage; this permits integration of propulsion generators into the overall power system. This second option is more relevant to a full ship design, and the simpler first option is probably preferable for the test programme.

7.2 SHAFT REVERSAL

Shaft reversal is effected by reversing polarity of the armature power supply either by discrete switchgear or a back-to-back thyristor controlled rectifier-arrangement.

Shaft braking is assisted by absorbing feed-back power through a braking resistor with switch S_4 open.

8. SYSTEM SERVICES AND MOTOR AUXILIARIES

A system function diagram (Fig. 6) shows the system equipment and services required, and these are described briefly below.

8. ARMATURE POWER SUPPLY

8.1.1 Prime Movers/Generators/Rectifiers

The prime movers, a.c. generators and rectifiers are discussed in Section 6 and the services required will depend on the types selected.

8.1.2 D.C. Bus System

To minimise losses the d.c. transmission bus system should be short as possible, the losses then depending on conductor current density. Losses and conductor weight per metre run for typical current densities are tabulated below, assuming high conductivity copper.

CURRENT DENSITY A/CM^2	DESIGN CURRENT kA	LOSS PER METRE RUN kW	WEIGHT PER METRE RUN kg
150	14.0	0.357	84
300	14.0	0.714	42
450	14.0	1.071	28
150	28.0	0.714	168
300	28.0	1.428	84
450	28.0	2.142	56

The design may be either air or water cooled.

8.1.3 D.C. Switchgear

Referring to Fig. 5, switches S_1 and S_2 are 260 V/14 kA rated, no-load operation; switch S_3 is 260V/28 kA rated, no-load operation, three position; S_4 is 260 V/28 kA, no-load operation; and S_5 is 260 V/28 kA, open no-load, close on-load. Actuator power will be required.

8.1.4 Braking Resistor

Dynamic braking absorbing propeller feed back and rotational energy is assisted by a braking resistor. Generally, this will be an air-cooled grid type in a cubicle with built in fan unit (Fig. 7). Particularly for icebreaker operation the resistor must accept frequent high energy injections. The design depends upon the propellor feedback characteristics and the braking/shaft reversing performance required (Ref. IRD 81/8). An a.c. supply will be required for the fan drive motor, possibly up to 25 kW.

8.2 MOTOR AUXILIARIES

8.2.1 Exciter

The overall excitation system is shown schematically in Fig. 8. Excitation is provided by a transformer/thyristor rectifier unit; the d.c. rating will be about 1.25 kA, the voltage about 10 V giving a charging time of about 8.5 minutes. Once charged the exciter will be intermittently operated and the average power consumption will be a fraction of the full rating of 12.5 kW. The exciter system in use at IRD is unsuitable for ship installation.

Coil protection is afforded by a permanently connected discharge resistor and a contact breaker. Dissipation of the stored energy of the inductor occurs when the circuit breaker is opened so that current flows in the resistor. With the circuit breaker closed the circuit resistance is low compared to the permanently connected resistor and the latter carries virtually no current.

The resistor in use at IRD is not suitable for ship installation and the type therefore proposed is visually similar to the braking resistor (Fig. 7), except that the resistor grids will have non-linear characteristics to minimise field coil discharge time. The cooling fan would require a drive of possibly 5 kW.

8.2.2 Helium Refrigerator/Liquefier System

A schematic arrangement of the system is shown in Fig. 9. The compressor (Fig. 10) supplies gaseous helium at about 10 bar to the cold box (Fig. 11) where the stream passes through a series of heat exchangers and an expansion stage to produce liquid helium to supply the motor field system cryostat; about 2% of the helium mass flow through the cold box is liquefied, the remainder, after counterflow cooling the heat exchangers, feeds back to the compressor at about 2 bar. The boil-off gas from the motor cryostat also feeds back to the compressor at about 2 bar. A buffer store at 2 - 10 bar is incorporated in the system to even out flows and provide a reserve of helium gas. The buffer store capacity is such that in the event of a quench of the superconductor, the sudden boil-off from the cryostat is contained in the system. The leakage rate from the system is very small, but it is advisable that a make-up supply be provided to cover 0.25 N m^3/24 h losses; this store can be in a standard high pressure gas cylinder with suitable regulating valve.

8.2.3 Vacuum Plant

The vacuum plant serving the motor cryostat comprises essentially an oil diffusion pump and a rotary roughing/backing pump plus associated valves and pipework. The oil diffusion pump and the high vacuum valve are mounted in the cryostat bore and the rotary pump (Fig.12) is outside of the motor.

8.2.4 Cover Gas System

The rotor operates within a sealed casing in a humidified inert gas atmosphere (slightly above one bar) contributing to the high brush/slipring performance; combined with this concept is a

brush debris removal system. The overall system is as shown in Fig. 13. A high pressure store of make-up inert gas (standard cylinder plus regulator) is advisable. Details of the blower, filter unit and duct work external to the motor are not yet settled but the blower unit is likely to be about 1.25 x 1.25 x 1.5mH.

8.3 SERVICES

Maximum demands for a.c. electrical power and cooling water are given in Tables 3 and 4 respectively. Actuator requirements are neglected at present, but supplies of compressed air will be required.

9. INSTALLATION NOTES

9.1 MOTOR

Two interfaces on the motor must be mutually agreed.

i. Output shaft, drive end bearing configuration
ii. Motor mountings

9.2 ITEMS CLOSE COUPLED TO MOTOR

There are two items which must be close coupled to the motor, as noted below:-

9.2.1 Coldbox

As shown on Fig. 11, using the existing liquid helium transfer line restricts the location of the coldbox in relation to the motor. No change is possible in the vertical relationship, but in plan the locus of the coldbox liquid helium delivery (point B) is an arc about Point A of radius 2403 mm. Also, the coldbox may be rotated about Point B. If this relationship cannot be achieved a new transfer line will be required.

9.2.2 Discharge Resistor

The discharge resistor must be coupled across the field current supply as close as possible to the field coil. If the resistor itself is located away from the motor the resistance of the connecting conductors must be considered in the resistor design.

9.3 OTHER ITEMS

Accepting in principle that the whole system should be compact and all conductors, pipework and duct work are suitable for their duty, the following items can be loated, as convenient, away from the motor.

i. Prime movers/generators/rectifiers.
ii. Switchgear
iii. Braking resistor*
iv. Low power exciter
v. Discharge resistor*
vi. Helium compressor
vii. Rotary vacuum pump
viii. Cover gas blower
ix. Cover gas filter
x. Cover gas humidifier

* The resistor units require a free flow of cooling air; also the exhaust air may be at over 100°C.

9.4 MOTOR EXTERNAL FIELD

Care must be exercised in positioning any item of equipment which could be adversely effected by the motor external field. One quadrant of the motor external field plot is shown in Fig. 14; superimposed on the plot is an outline of the non-drive end of the motor. It should be noted that the field plot is for free space and the influence of iron is ignored; the field shown will therefore be modified when installed in the ship.

TABLE 1

SYSTEM COMPONENT SCHEDULE

ITEM	DESCRIPTION	RATING	DIMENSIONS m	WEIGHT TONNES	NO. OFF
1	Prime mover	3.75 MW	-	-	2
2	Coupling	-	-	-	2
3	Generator/exciter	3.75 MW	-	-	2
4	A.C. bus	-	-	-	2 sets
5	Rectifier	260V/14kA d.c.	-	-	2
6	D.C. bus	14kA/28kA	-	-	1 set
7	D.C. switchgear (Fig. 5)				
	a. Gen/rect isolator	260V/14kA d.c.,no-load operation	-	-	2
	b. Reversing switch	260V/28kA d.c., no-load operation	-	-	1
	c. Braking switch	260V/28kA d.c.,no-load operation	-	-	1
	d. Propulsion isolator	260V/28kA d.c., open no-load/close on-load	-	-	1
8	Braking resistor (Fig. 7)	-	1.0x1.0x2.0	1.0	1
9	Propulsion motor* (Fig. 1)	Table 2	5.6LX3.6W X3.1H	60	1
10	Motor exciter (Fig. 8)				
	a. Transformer/ rectifier	10V/1.25kA d.c.	-	-	1
	b. Discharge resistor (Fig. 7)		1.0x1.0x2.0	-	1

	c. Contact breaker	1.6kV/1.25kA d.c.	-	-	1
	d. Cable	1.25kA	-	-	1 set
11	He refrigerator (Fig. 9)				
	a. Compressor* (Fig. 10)	46g/s He 10 bar		6.0	1
	b. Cold box* (Fig. 11)	1.0g/s He		1.5	1
12	Vaccum system				
	a. Oil diffusion* pump		Inside motor		
	b. High vacuum* valve		Inside motor		
	c. Rotary pump*	-	1.32x0.94 x0.78H	0.522	1
	d. Pipework	-	-	-	1 set
13	Cover gas system (Fig. 13)				
	a. Gas blower* (excl. motor)	-	1.25x1.25 x1.5	0.4	1
	b. Humidifier*	-	-	-	1
	c. Filter unit*	-	-	-	1

* will be available from IRD

TABLE 2

PROVISIONAL MOTOR SPECIFICATION

Rated power output	5.86 MW
Rated back e.m.f.	223 V
Input voltage	252 V
Input current	27.3 kA
Rated speed	162 rev/min
Efficiency	85.17%

Dimensions (Fig. 1)

Length	5.68 m
Breadth	3.6 m
Shaft centreline height, minimum	1.3 m
Height overall	3.1 m
Weight	60 tonnes
Rotor weight	22 tonnes
Rotor polar inertia	2.7×10^4 kg m^2

TABLE 3

ELECTRICAL SERVICES - A.C.

ITEM	DESCRIPTION	MAXIMUM POWER, kW	CONTINUOUS POWER, kW
1	Generator exciters	?	?
2	Braking resistor cooling fan	25	-
3	Cover gas blower	25	25
4	Vacuum plant:		
	Rotary pump	5.6	-
	Oil diffusion pump	2.25	-
5	Helium compressor	140	140
6	Discharge resistor cooling fan	5	-
7	Low power exciter	12.5	1.0

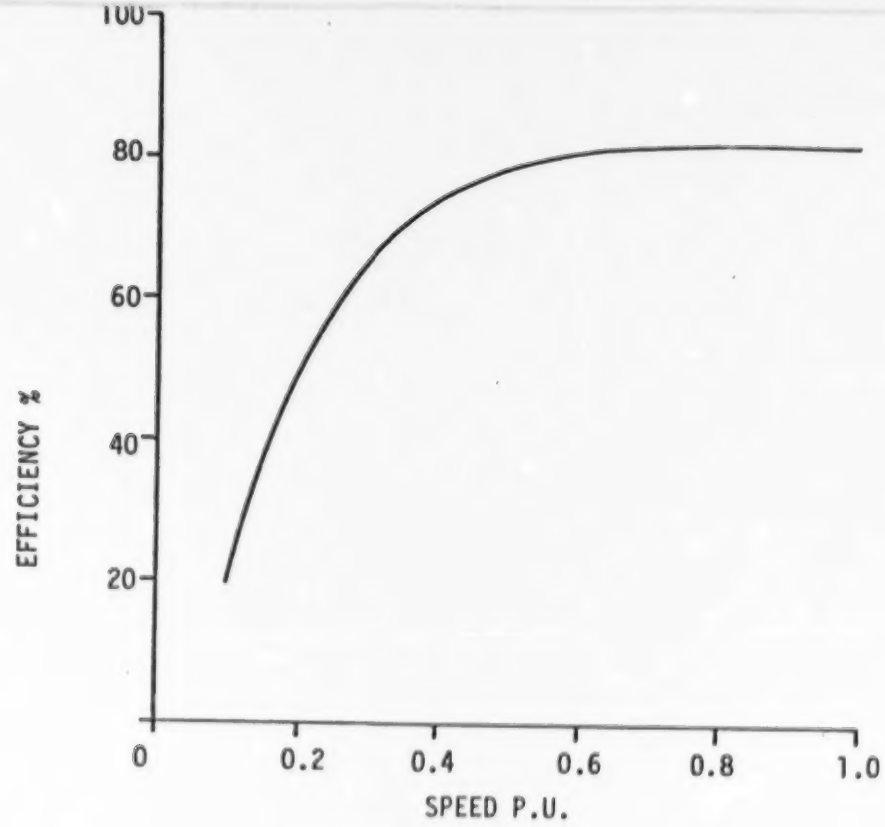
TABLE 4

COOLING WATER SUPPLIES

ITEM	DESCRIPTION	MAXIMUM DEMAND	CONTINUOUS DEMAND
1	Propulsion motor, demineralised	120 litres/ second (1585 gall/min)	Current dependent
2	Vacuum oil diff. pump, FW	3 litres/minute (0.66 gall/min)	-
3	Vacuum rotary pump, FW	2 litres/minute (0.44 gall/min)	-
4	Compressor/heat exchangers, FW	3.6 litres/second (48 gall/min)	3.6 litres/ second (48 gall/min)

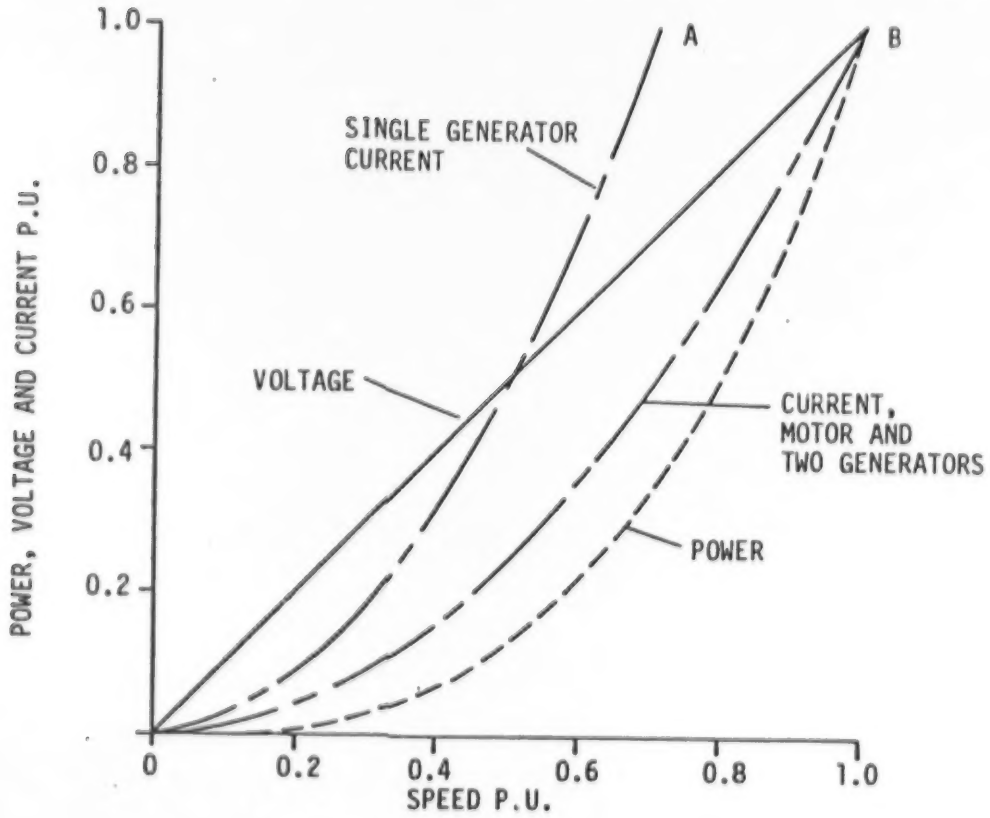
MOTOR OUTLINE DIMENSIONS

FIG. 1



EFFICIENCY vs SPEED (CUBE LAW)

FIG. 2



POWER, VOLTAGE AND CURRENT vs SPEED

FIG. 3

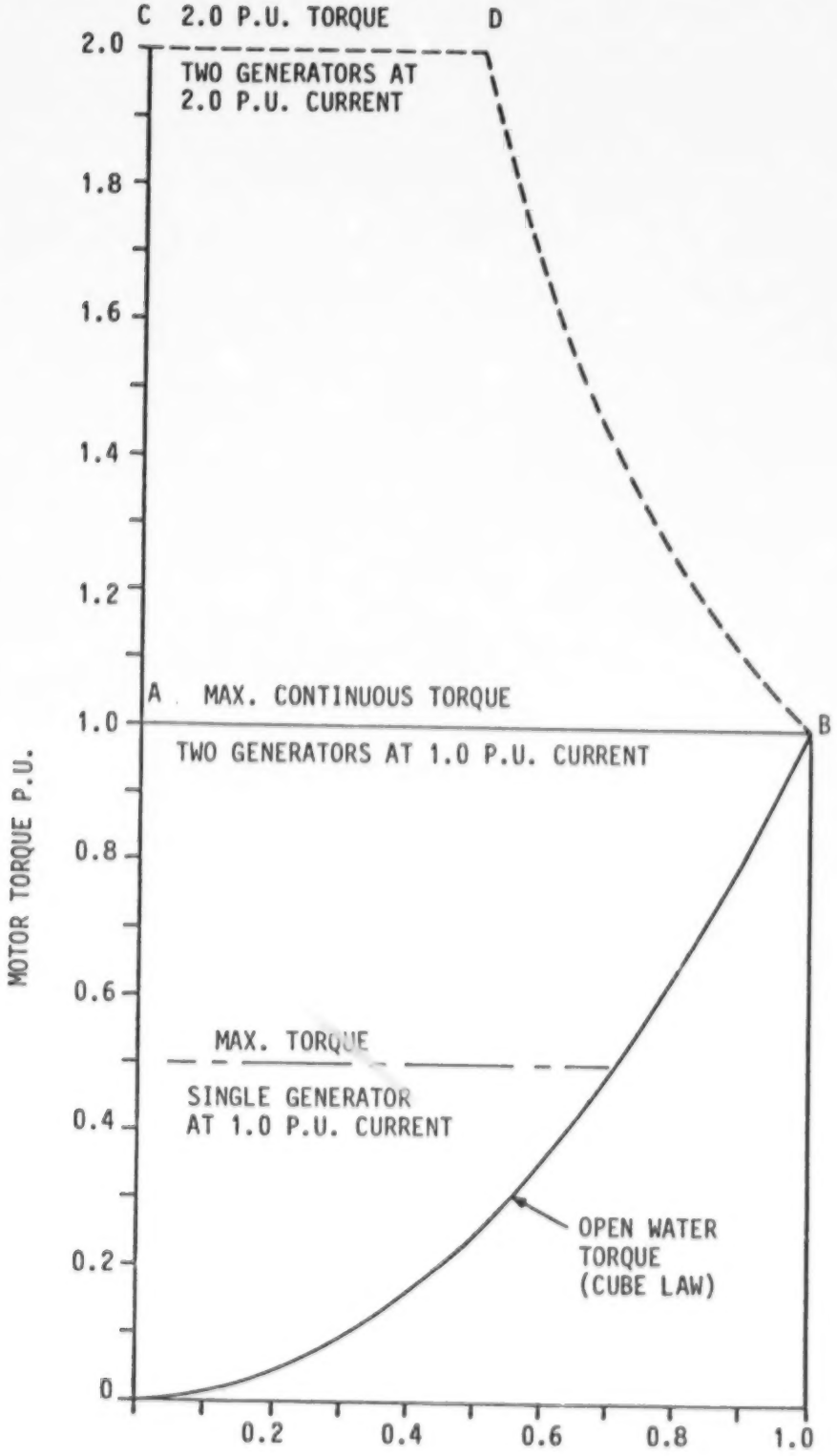
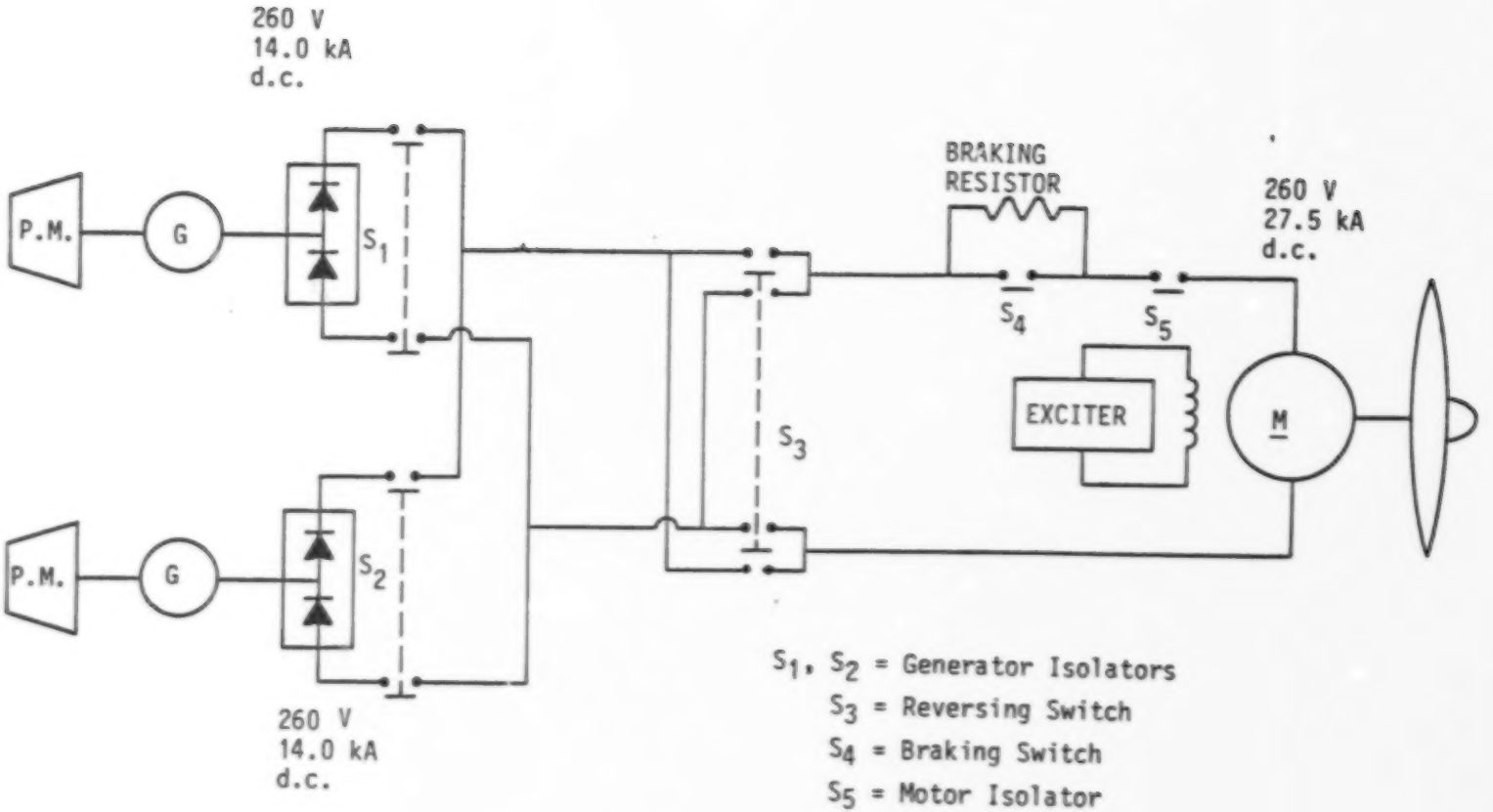
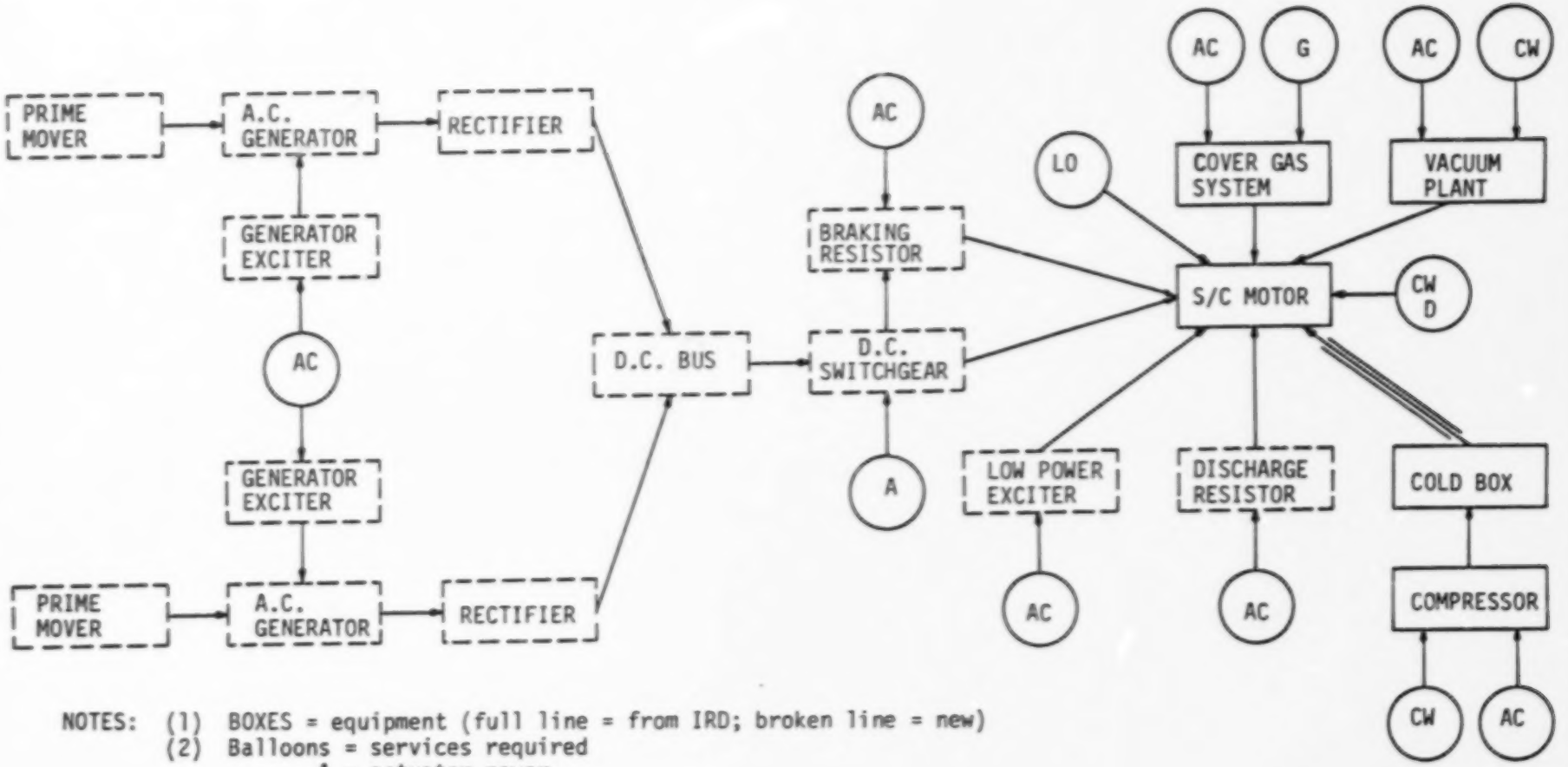

C 2.0 P.U. TORQUE
D
2.0
TWO GENERATORS AT
2.0 P.U. CURRENT
1.8
1.6
1.4
1.2
A MAX. CONTINUOUS TORQUE
1.0
B
TWO GENERATORS AT 1.0 P.U. CURRENT
0.8
0.6
MAX. TORQUE
SINGLE GENERATOR
AT 1.0 P.U. CURRENT
0.4
OPEN WATER
TORQUE
(CUBE LAW)
0.2
0
MOTOR TORQUE P.U.
0.2
0.4
0.6
0.8
1.0
1.0 P.U. torque = 345 kN m
1.0 P.U. speed = 162 rev/min
MOTOR TORQUE VS SPEED

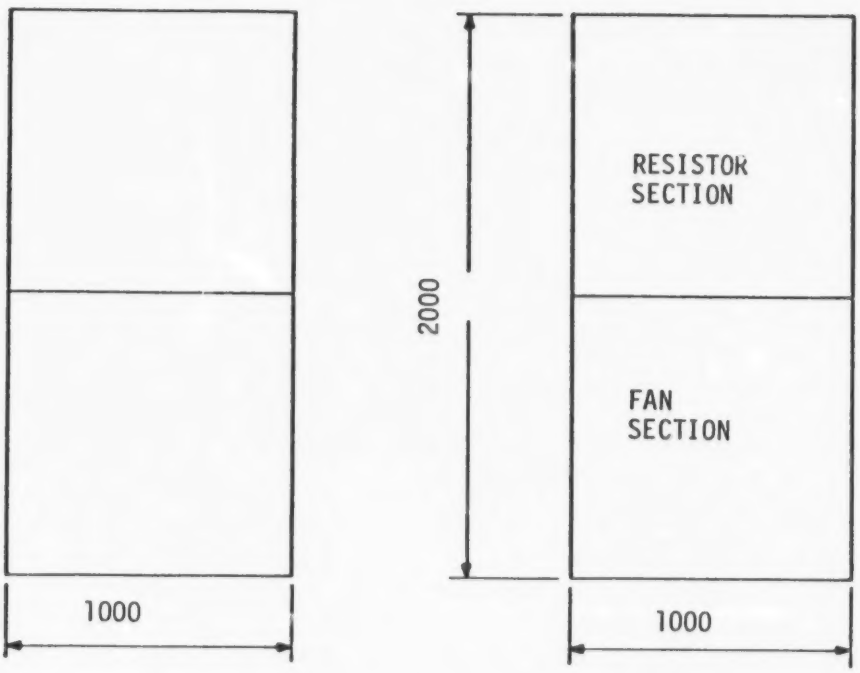
FIG. 4



OUTLINE PROPULSION SYSTEM



NOTES: (1) BOXES = equipment (full line = from IRD; broken line = new)
(2) Balloons = services required
A = actuator power
AC = a.c. electrical power
CW = cooling water (D = demineralised)
LO = lubricating oil
G = cover gas make-up
(3) Line marked ═══ to be short as possible

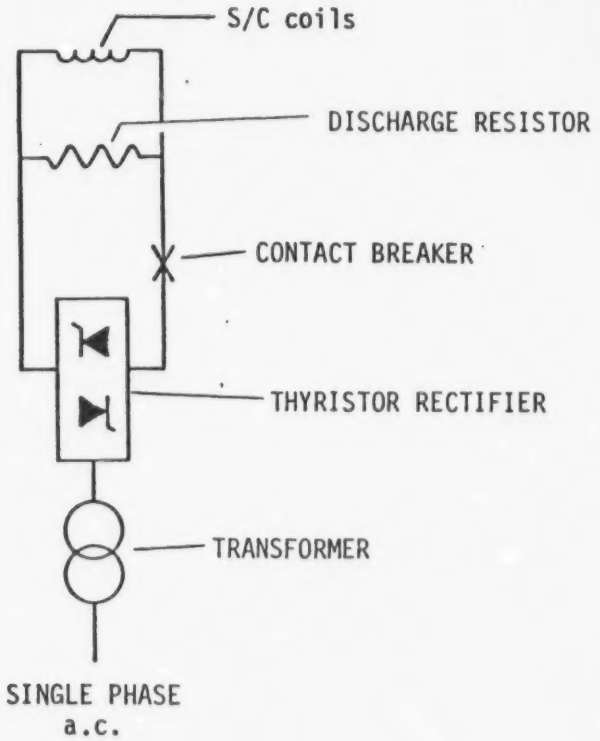


DIMENSIONS mm

WT = 1 tonne approx

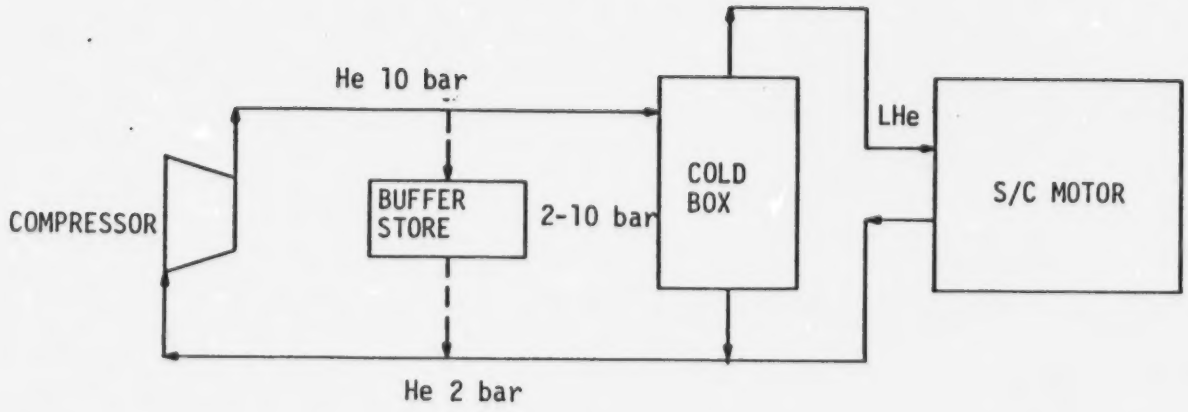
RESISTOR UNIT

FIG. 7



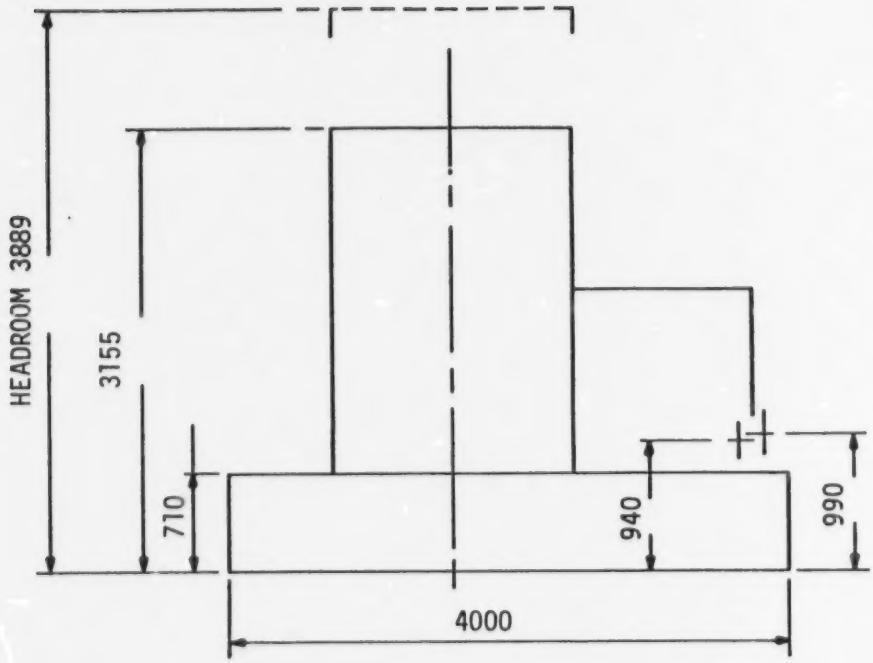
EXCITER SYSTEM SCHEMATIC

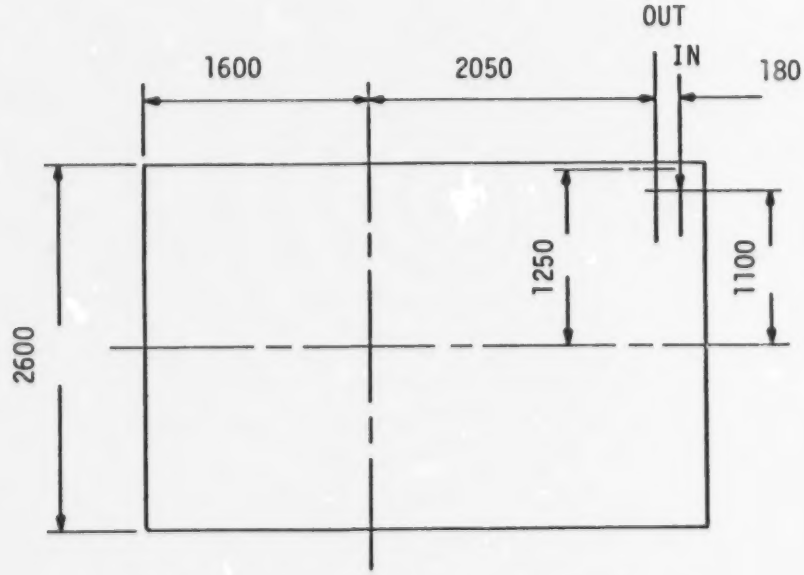
FIG. 8



HELIUM REFRIGERATOR/LIQUEFIER SYSTEM

FIG. 9

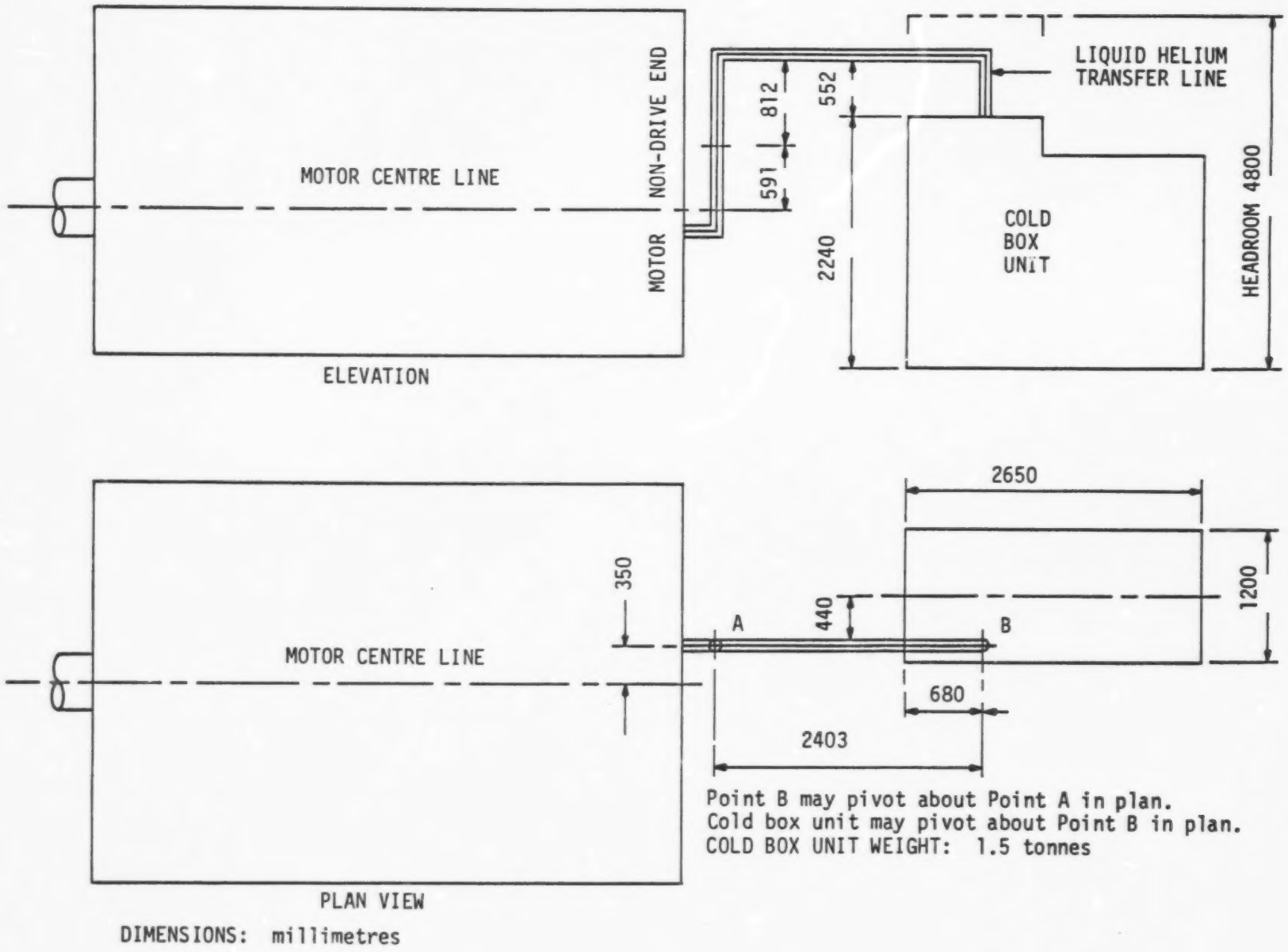




COMPRESSOR UNIT WEIGHT: 6 TONNES
DIMENSIONS: millimetres

HELIUM COMPRESSOR INSTALLATION DATA

FIG. 10

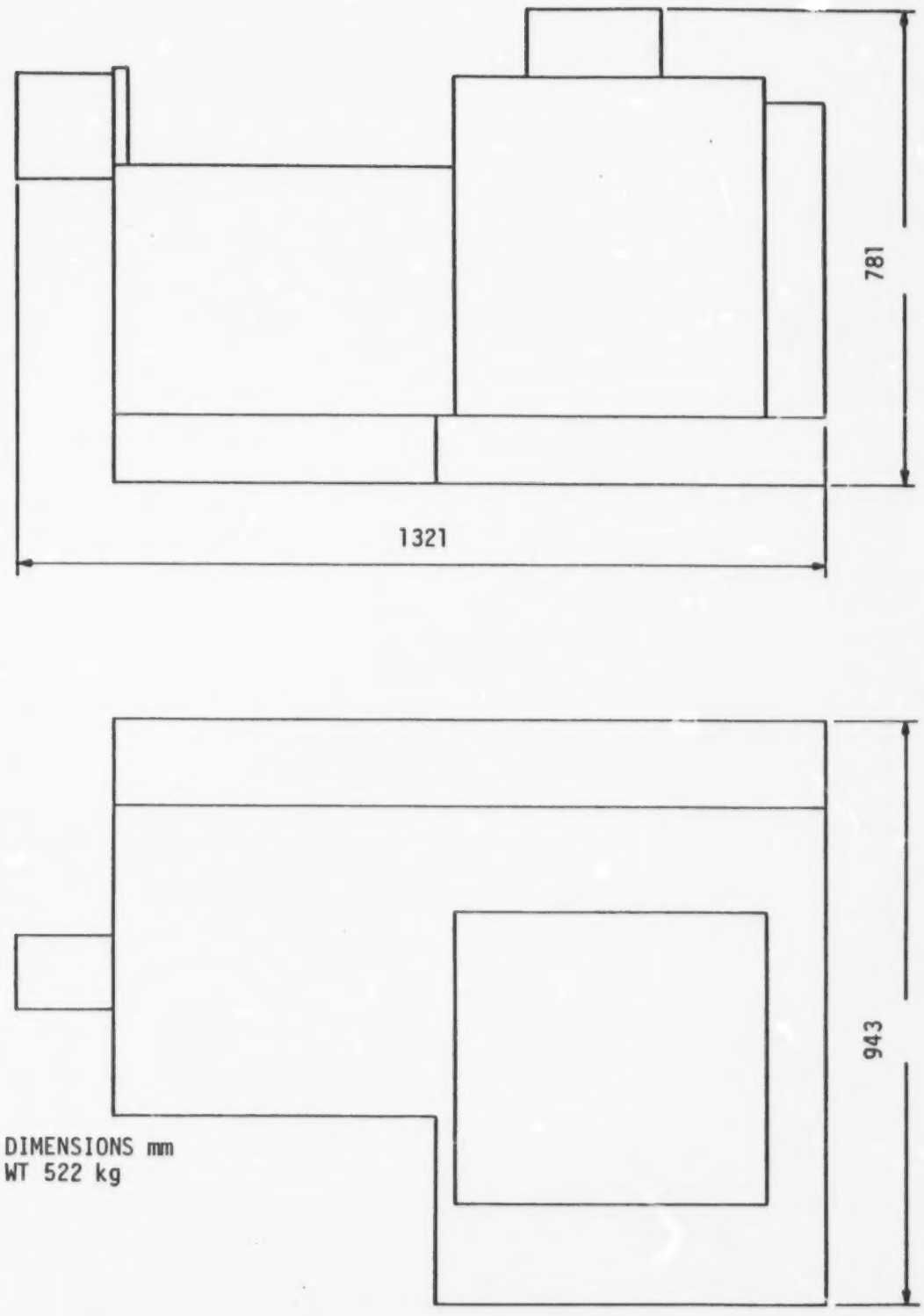


Point B may pivot about Point A in plan.
Cold box unit may pivot about Point B in plan.
COLD BOX UNIT WEIGHT: 1.5 tonnes

DIMENSIONS: millimetres

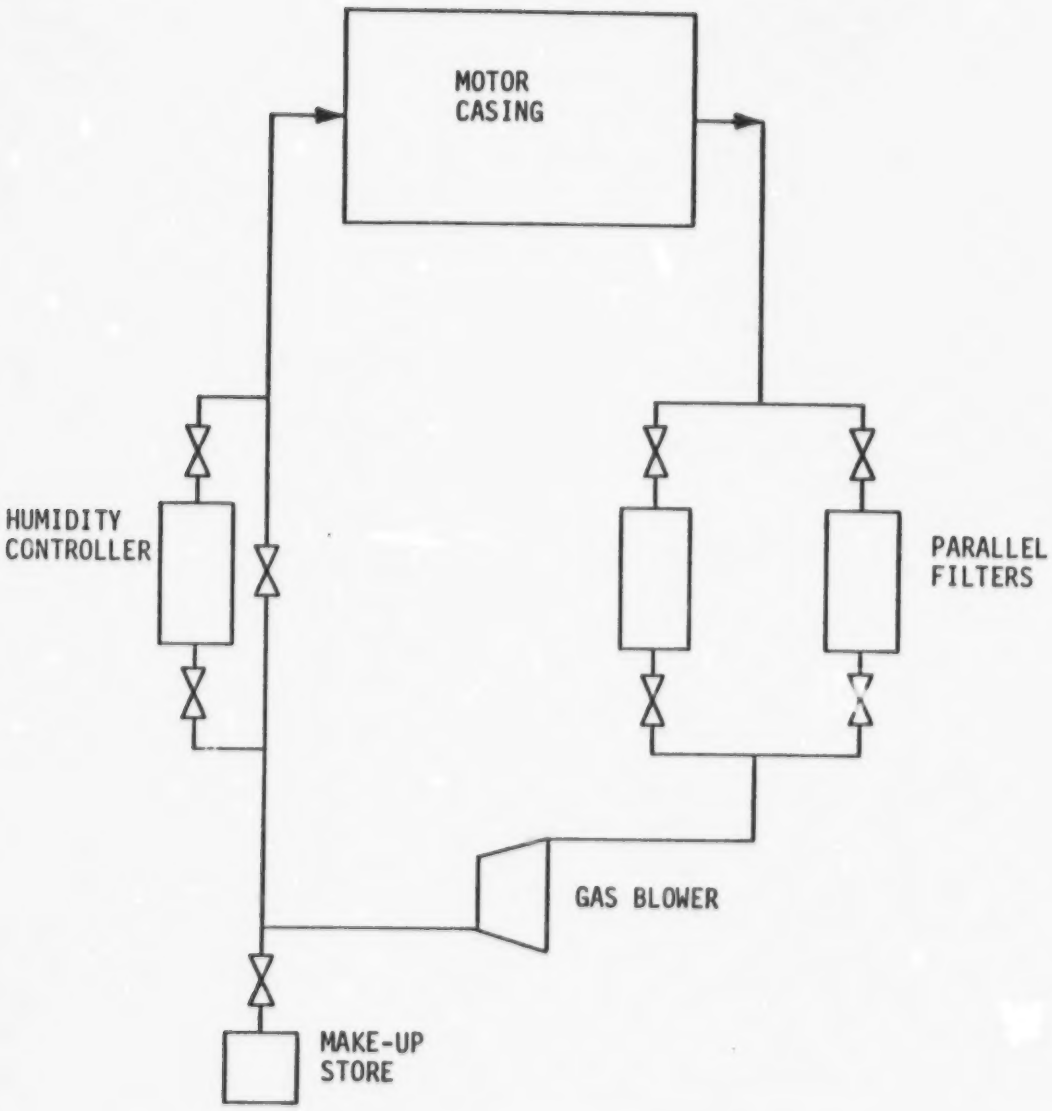
EXISTING COLD BOX UNIT AND TRANSFER LINE INSTALLATION DATA

FIG. 11



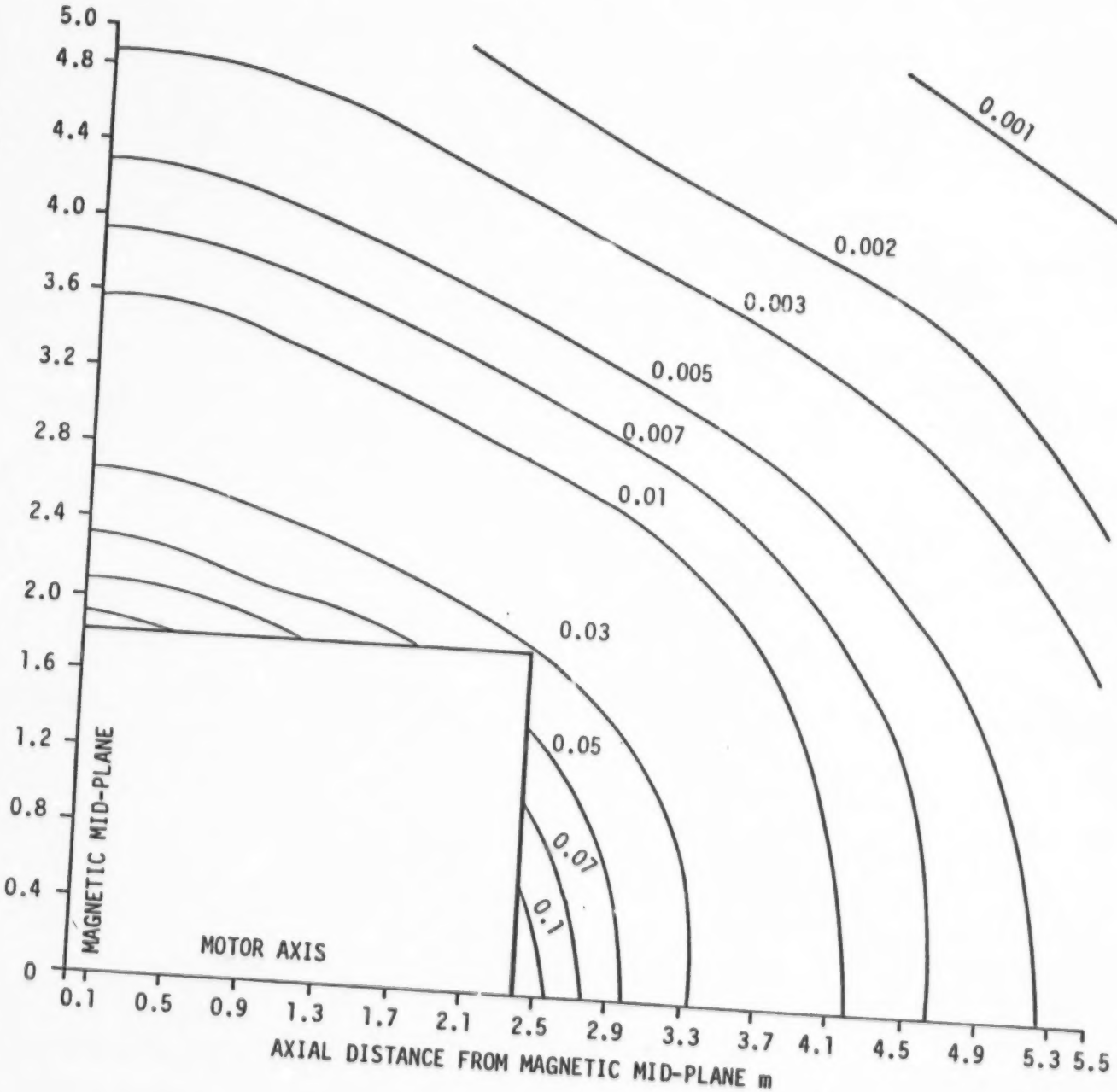
ROTARY VACUUM PUMP

FIG. 12



COVER GAS SYSTEM

FIG. 13



MOTOR EXTERNAL FIELD, TESLA
(FREE SPACE)

APPENDIX 2

OUTLINE CONVERSION DRAWINGS ACCOMPANYING

FUNCTIONAL SPECIFICATIONS (SECTION 5)

1290C-1	ITEMS TO BE REMOVED	- Floor Plate Level of Engine Room
1290C-2	ITEMS TO BE INSTALLED	- Floor Plate Level of Engine Room
1290C-3	ITEMS TO BE REMOVED	- Generator Flat Level
1290C-4	ITEMS TO BE INSTALLED	- Generator Flat Level

MAPS NOT

FILMED

CARTES

OMISES